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Advances in graphic display technologies have made virtual reality (VR) and scientific visualization applications accessible to a wide user population. Unfortunately, few human interface tools exist to allow users to interact naturally with these powerful graphical environments. To address this need, Immersion Corporation has developed a user interface mechanism to allow natural manual interaction with 3-D environments which provides realistic *force feedback* to the user. This haptic display methodology combines high fidelity, low cost, and inherent safety to allow force reflection technology to become commercially feasible.

The long term objective is to produce a 3-D haptic interface for virtual environments. Phase I focused on producing one-dimensional haptic interface hardware and incorporating this technology into a real world VR application. Immersion and the Ohio Supercomputer Center have worked together to produce a virtual simulation of epidural analgesia, a medical procedure that requires delicate needle insertions into the spinal column. The resulting VR simulation is so realistic in *look* and *feel*, it can actually be used as a training environment to teach doctors to perform the dexterous manual procedure, allowing them to learn manual technique and explore the associated physical sensations without the risks or costs associated with using real biological specimens.

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FINAL TECHNICAL REPORT

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Our six-degree-of-freedom haptic display has immediate commercial applications in the medical simulation and scientific visualization fields. The technology is also applicable to every form of computer interface, including computer-aided design packages, scientific modeling, entertainment, and educational tutorials.

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A. Identification and Discussion of the Effort

A.1 Background: New Opportunity for Haptic Display Development

In recent years, advances in graphic display technology have made possible the rapid and economical generation of high fidelity, three-dimensional images. From virtual reality to scientific visualization, the potential applications of high fidelity 3-D computer environments span the gamut from military training to surgical simulation. Unfortunately, the recent technological advances in visual information display have not been adequately supported by innovative means of interfacing humans to computers. Very little progress has been made towards developing human interface tools that allow users to perform natural manual interactions with 3-D computer environments. Just as the computer "mouse" empowers users to perform natural manual interactions with 2D environments, new human interface technologies are now needed to empower users to interact naturally with 3-D virtual environments.

To allow users to execute natural manual interaction with 3-D virtual environments, two primary issues must be addressed when developing effective human interface technologies. These two issues can be classified simply as *manual input* and *manual feedback* respectively. The first of these, manual input, requires the development of human interface technologies that allow users to execute natural and comfortable gestures in 3-D space with minimal fatigue and optimal dexterity. Immersion Corporation produces a number of products for 3-D input and manual control. For cursor control and arbitrary manual input tasks, we sell the Immersion PROBE, a six-degree-of-freedom tracking device which uses an articulated arm to track and support motion.

The second issue which needs to be addressed is *manual feedback*. Known as "haptic display" or "force feedback", the ability to provide users with realistic "feel" information about the virtual environment they are interacting with is one of the most challenging human interface problems facing researchers today. To date, only a handful of human interface devices have been developed which provide users of virtual environments with force feedback. Without exception, these devices have been developed as research tools, with price tags which put them out of the reach of the user population. As a result, the commercialization of haptic display technology has been negligible. Potential user s such as engineers, designers, scientists, and medical professionals who could benefit greatly from addition of force feedback to their virtual simulations have not had access to such technologies. To address this need, Immersion Corporation intends to develop the first commercially viable, high performance, haptic interface tool for manual interaction with 3-D virtual environments.

A.2 The Nature of the Project

If this project continues through Phase II, we plan to develop a six-degree-of-freedom user interface which will not only be an input device for commanding position and orientation of a cursor in a 3-D information space, but will also be an output device which reflects physical forces back to the user. Such a *haptic display* interface would be capable of presenting physical properties of the 3-D information space by representing surfaces and contours with actual physical forces. Although a handful of force-reflecting devices are currently available to large research laboratories, the typical approach to force reflection has resulted in interface hardware

which is so complex and expensive that it can only be used by trained personnel in elite research facilities devoted to studying force reflection. These devices are therefore out of reach for the end users who would benefit most from such haptic display tools -- scientists, engineers, medical professionals, and designers.

We at Immersion Human Interface Corporation have taken on the challenge of bringing force reflection technology out of the research lab and onto the desks of scientists and engineers. To accomplish this important step, we have developed a *hybrid* approach to force reflection which will turn haptic display hardware into economically feasible commercial products for mainstream use. The details of our hybrid haptic display methodology will be discussed in detail later in this document.

A.3 Phase I Overview

Immersion Corp. used Phase I to tackle a subset of the overall technical challenge by developing a *single-degree-of-freedom* haptic display for *one dimensional* interaction. This single degree of freedom system, while much simpler than the ultimate 6-degree-of-freedom system proposed for Phase II, has afforded an excellent feasibility study for the final system by allowing us to test and refine our innovative approach to force reflection before proceeding to Phase II. The Phase I project has also resulted in an immediately applicable haptic interface for an important real world application. We are encouraged by the success of our Phase I single degree-of-freedom haptic devices, which not only demonstrate the prowess of our haptic display methodology, but also demonstrate the commercial potential of force reflection technology in general.

This powerful real-world application mentioned above is a virtual reality system developed to train doctors to perform a delicate one-dimensional medical procedure known as *epidural analgesia*. This medical simulator was developed as a joint effort between Immersion Corporation and experts in the field of medical simulation and training at Ohio Supercomputer Center. In order to create an effective simulation, we developed a single-degree-of-freedom haptic interface which is optimized to display the force information associated with such medical procedures. The end product of our Phase I effort, the *Virtual Epidural Simulator*, acts as a very powerful proof of concept of our force reflection technology, not to mention an immediately applicable technology. Extending this technology to three-dimensional space in Phase II will allow us to simulate more complex medical procedures such as laparoscopic surgery.

Virtual Epidural Simulator

(A single-degree-of-freedom virtual simulation with force feedback);

Epidural analgesia is one of the most frequently used techniques for the relief of pain during surgery. In most hospitals that have an obstetric anesthesia service, epidural analgesia is the most prominently used anesthesia technique for vaginal childbirth and cesarean section. The procedure involves the injection of a local anesthetic or an opiod into the epidural space of the spinal column. Although a single degree-of-freedom task, it is a delicate manual operation which requires the surgeon to guide a catheter into the epidural space using only haptic cues to guide the needle. By feeling the needle passing through various tissues, the doctor needs to maneuver it into the correct space without

damaging the spinal cord in the process.

One major problem with this procedure is that there currently exists NO way of training residents on this dangerous manual task without actually having them learn on live patients. By creating a virtual simulation of this procedure, Immersion Corporation and Ohio Supercomputer Center have produced an invaluable tool for training doctors to perform this vital task. The simulator includes a force-reflecting interface which generates the appropriate haptic cues associated with needle penetration of the various layers of muscle and tendon. The *Virtual Epidural Simulator* provides a trainee with a believable, non-threatening environment which encourages the free exploration of the many variances confronted in administering a lumbar epidural. Such interaction and exploration with a virtual simulation should increase the residents understanding of the anatomy and intricacies encountered in the epidural procedure. It is hypothesized that such a training environment will reduce resident anxiety and limit the number of trials required to learn to successfully deliver regional anesthesia through the epidural method.

In the Phase I effort, Immersion Corporation focused on the development of the force reflection hardware required for the virtual simulation of the epidural procedure, while Ohio Supercomputer Center developed the graphic simulation of the procedure by providing high level software support and by providing direct exposure to medical personnel who can provide performance evaluations of the hardware. Together Immersion Corp. and Ohio Supercomputer Center formed an effective team to develop and evaluate the single-degree-of-freedom haptic interface system.

B. Technical Objectives of the Effort

Shown in bold are the technical objectives as stated in the Phase I proposal.

Design and construct a single-degree-of-freedom haptic display, complete with sensor elements and force reflecting elements that can generate controllable passive resistance and controllable active force output. This system must have the fidelity required to accurately reproduce the haptic sensations associated with medical procedures such as epidural analgesia.

The primary objective of the Phase I proposal was to develop a one-degree-of-freedom haptic display that can be extended to a full six-degree-of-freedom haptic display in Phase II. The one degree of freedom haptic display was targeted at simulating the feel of a specific medical procedure, epidural analgesia.

Before designing and building the device, testing was performed with an instrumented probe to discover the bandwidth and magnitude of haptic sensations required by medical procedures and by haptic interactions in general. A piece of hardware was constructed which combined a six-degree-of-freedom tracking probe connected to an epidural needle that was instrumented with a high fidelity force sensor. Using this specialized hardware, skilled doctors could perform epidural procedures on cadaver specimens while position and force data was recorded. By recording the three dimensional location of the needle and the forces generated

on the needle during the insertion procedure, we were able reconstruct the force profile associated with the epidural procedure. Extensive testing was performed on cadaver specimens to quantify the force profile and frequency content of haptic sensations representative of epidural needle insertion into the spinal column. Analysis of this data was extremely useful in guiding the design of the virtual reality system to simulate such haptic information.

In addition to the direct force/position measurements during actual manual epidural procedures, CT scan data recorded taken from the operative site of the cadaver specimen. Analysis was performed to assess if force profile information could be correlated with the CT scan data. The ultimate goal is to establish a methodology where virtual reality simulations of haptic sensations can be derived directly from volumetric data such as CT or MRI scans.

Once testing was complete, our next step was to construct two versions of a simple single degree-of-freedom force reflecting device. The first one of these was a passive device, using magnetic particle brakes to provide resistance to motion. A second device was constructed as well which incorporated a linear capstan drive mechanism and an active servo motor for actuation. These two devices were constructed so that active and passive force feedback techniques could be compared and contrasted.

Develop integrated Virtual Epidural Simulator and Assess Effectiveness

The hardware mentioned above was sent to OSC for integration into a single degree-of-freedom surgical simulation. The device using servo motors was used to construct the Virtual Epidural Simulator. For the simulator, OSC developed high-level software, including graphics, user-interface, and simulation capabilities to integrate the one-degree-of-freedom haptic device into their medical simulation application. The resulting full system of hardware and software provides a fully functional virtual simulation of the epidural procedure. This simulation provides the appropriate haptic sensations associated with needle penetration of the various types of tissues encountered during such a procedure.

Ongoing tests with medical practitioners has provided data on performance and effectiveness for specific haptic sensations.

The Phase I effort resulted in a complete simulation system which combines a convincing haptic experience with an intricate simulation of the medical procedures. The success of Phase I clearly warrants a Phase II effort by demonstrating the applicability of our force feedback technologies to medical simulation. In addition to demonstrating the general effectiveness of adding force feedback technologies to virtual reality simulations, this Phase I effort demonstrated the kinematic limitations of the Phase I single-degree-of-freedom device and thus strongly suggests that the full six-degree-of-freedom device should be pursued in Phase II.

Develop a design specifications document which enumerates the optimal parameters for a stylus-based haptic display. Such a document will list appropriate design parameters such as size, mass, inertia, allowable friction, balance, range of motion, and resolution

for a mechanical system that supports haptic display. Such a document will also enumerate the requirements for a hybrid haptic display such as bandwidth, maximum resistance forces, and latency requirements.

One important step that is often overlooked in the design of human interface hardware is quantifying the *perceptual* requirements of the user. Our final objective is not simply to produce a haptic interface tool with technical merit, but also to produce one that conforms well to appropriate specifications for a system with a human in the loop. Since there are no widely accepted design specifications for systems that support manual interaction within immersive computer environments, an important part of Phase I has been to determine some appropriate specifications for the human-computer system we intend to complete in Phase II. The fidelity of a force feedback system depends on the accuracy of the sensors, the processing speed of the central computer, the performance of the actuators, and the transparency of the mechanical transmission. The contribution that each of the above sub-systems has upon system performance is discussed in great detail in Appendix A: Design Specifications Document.

C. Phase I Statement of Work Completed

Phase I efforts have proceeded along three fronts:

1. Immersion Corporation developed force feedback hardware using both passive and active technologies as laid out in our original proposal. This hardware was sent to OSC for integration into the full virtual reality medical simulation platform. In addition, Immersion constructed other prototype hardware for in-house evaluation.
2. Immersion analyzed the performance of the force feedback hardware prototypes and analyzed the data resulting from OSC's testing efforts.
3. OSC has been exploring simulation techniques, including graphics, interaction techniques, MRI and CT data processing, and haptic presentations.

These efforts are described in detail in the following pages.

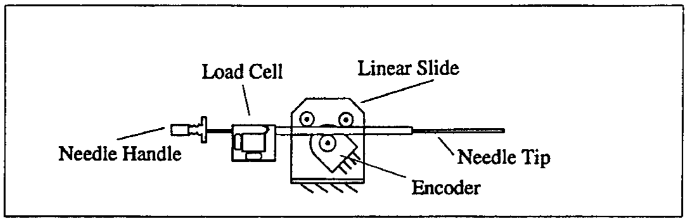
C.1 Hardware Developed

First Prototypes of 1 degree-of-freedom haptic interface

Single Degree-of-Freedom Active System

Force and position sensing development hardware is needed to devise models to be used in the position sensing and force producing product hardware. This hardware is described below and a full characterization of the hardware is presented in Appendix C.

Haptic Sensing Hardware



Haptic Feedback Hardware

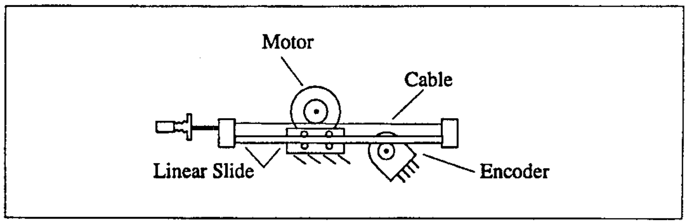


Figure C-1: *Hardware*

Figure C-1 shows both the haptic sensing hardware and haptic feedback hardware. The haptic sensing hardware is essentially an instrumented epidural needle. The epidural needle has been mounted on an extra long lightweight handle, which is constrained to linear motion without twist by a set of high quality bearings. A small strain gage-outfitted load cell which has been Electro-discharge-machined out of aluminum comprises the force sensor. The amplification circuitry is located right next on the load cell on surface mount printed circuit board. An in-house design 16-bit A/D converter and a low-cost digital I/O card allow for acquisition of the force signal by a 486DX2-66 PC. Finally, a 1024 count/revolution rotary encoder with a friction drive wheel on the needle handle is responsible for transducing the position of the needle.

The hardware for the haptic feedback product is made up of a linear slide, motorized through a capstan drive by a low-inertia precision motor. A highly flexible steel cable takes 3 turns around a screw pulley on the motor. For simplicity and low cost, we have decided not to include a force sensor in the final product. Therefore, measured force will not be available for use in a control law or table lookup scheme. An encoder is again responsible for tracking position of the slide. To minimize inertia, the rod itself moves and the platform is fixed.

The haptic sensing and feedback hardware is used in three configurations. A sensing hardware is used alone with tissue substitute samples to generate simulation models. The sensing hardware is then used together with the feedback hardware to test candidate models. Finally, the feedback hardware alone will constitute the simulator.

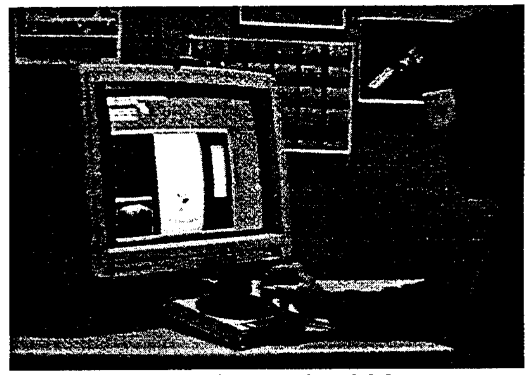
Single Degree-of-Freedom Needle Insertion Simulator

Immersion produced a single degree-of-freedom needle insertion simulator to provide OSC with a start on their simulation efforts. The device, shown below in Figure C-2 uses a

passive resistance device to apply resistive forces to a needle. The hardware is accessed by the computer through a standard serial port, providing relatively low-bandwidth I/O.

The device allows a needle to be inserted and withdrawn into a block which can be programmed to provide resistive forces upon demand to simulate forces. The results obtained by OSC can be found in section C.3.

Needle Insertion Simulator



Device Being Used at OSC

Figure C-2: *Passive Single Degree-of-Freedom Needle Insertion Simulator*

Instrumented needle to send to OSC

A 5 pound single-axis tension/compression load-cell (model ALD-MINI-UTC 0.5" from A.L. Design in Buffalo, NY) was built into a needle sent to us by OSC. The needle was cut along a central cross-section and the sensor was inserted to measure forces along the axis of the needle. The instrumented needle was then attached to the Immersion Probe (see next section) to track its position along with the needle forces.

Immersion Probe™

The Immersion Probe is a six degree-of-freedom articulated arm which can be used to track the position and orientation of a stylus in 3D space. Since all six degrees-of-freedom are reported, the device can be used as a general-purpose manipulation tool. OSC used the device to report the position and orientation of the instrumented needle described above in real time. See Figure C-3 for a look at the procedure.

Figure C-3: *Immersion Probe (left) & Immersion Probe being used with the Instrumented Needle (right)*

Second Prototype: 1 Degree-of-Freedom Impulse Engine

To provide OSC with a high performance single degree-of-freedom force reflecting system, Immersion designers assembled the second prototype, which consists of a linear capstan drive mechanism coupled to a servo motor. Electronics are interfaced to the computer via the PC bus. The following subsections outline the capstan design and the electronics design.

The Linear Capstan Design:

The basic linear axis consisted of a precision ground shaft which slid prismatically through a Teflon coated bearing surface. A high tension aircraft cable was fixed to either end of the linear shaft and was wound around a small diameter *capstan pulley*. This pulley was fixed to the drive motor and thus power to the motor applied linear force to the shaft. An optical encoder was mounted on the servo motor to monitor the position of the linear axis. This configuration achieved the required force output and required range of motion while maintaining low friction, high stiffness, and negligible backlash. The configuration allowed the linear drive to be tracked with the required accuracy in position. The final linear drive system, as shown below in Figure C-4, resulted in a smooth drive mechanism which could produce high bandwidth haptic sensations and introduced minimal noise.

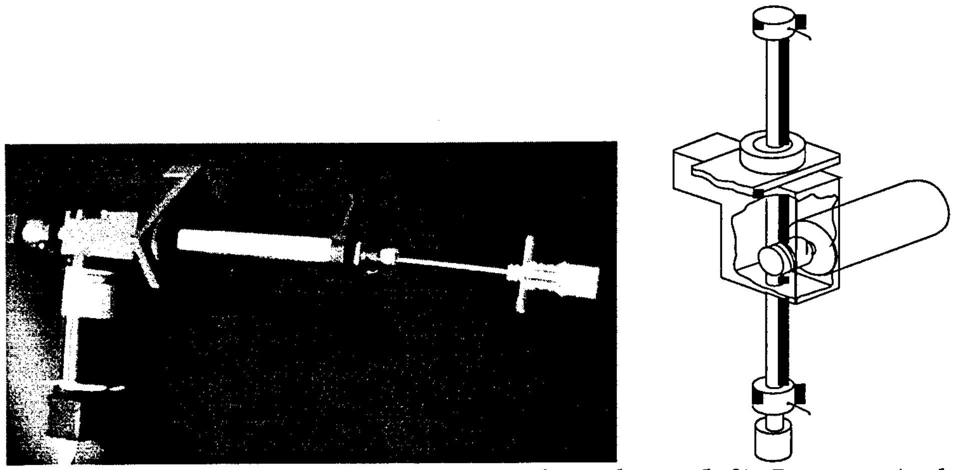


Figure C-4: *Linear Capstan Design: Actual Hardware (left), Drawing (right)*

Electronics: Interface and Drive Circuits

We have developed an electronics architecture which allows a standard PC computer to interface with our force feedback hardware. This architecture, shown in Figure C-5, can be broken up into a number of subsystems which include an ISA CARD, a POWER AMPLIFIER, and the SENSOR/ACTUATOR subsystem. The ISA CARD is the central component which allows the other subsystems to interface with the mother board of the host computer. The POWER AMPLIFIER provides power to the actuators, based on the low level force command signals produced by the ISA card. These power amplifiers use their own power supply to remain independent of the host computer and to provide maximum performance. Finally, the sensors and actuators in the SENSOR/ACTUATOR subsystem provide the position input and force output respectively for the user interface.

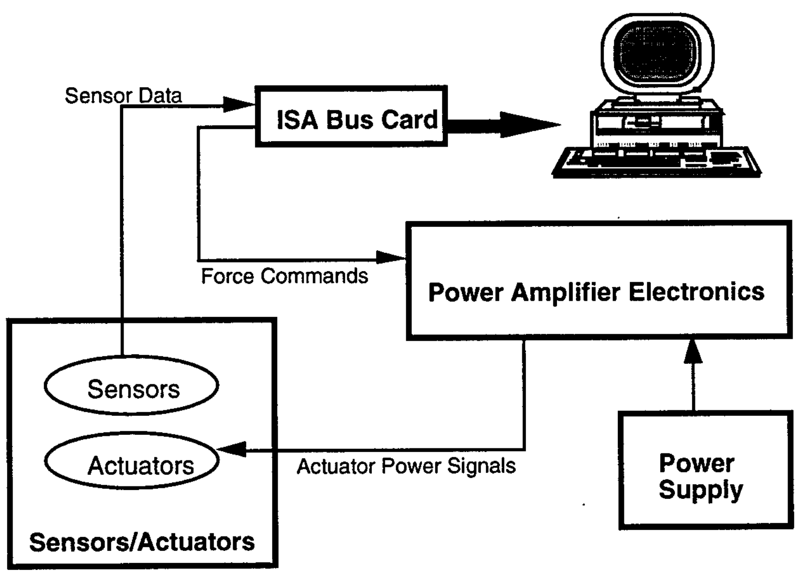


Figure C-5, Electronics Design Overview

For a detailed description of each of these subsystems, see Appendix E.

C.2 Analytical Studies Performed at Immersion

Evaluation of typical forces in haptic encounters

In an earlier effort at Immersion, psychophysical testing was performed on human subjects to reveal the minimum performance requirements of a stylus-based haptic interface. The goal was to use the limitations in human perceptual abilities as a governing factor in determining the maximum hardware requirements. Physical bandwidth and maximum force output were the hardware parameters we chose to minimize such that the perceptual fidelity of the haptic sensations would not be significantly degraded. Testing revealed that an effective stylus-based haptic interface does not need to provide the user with an effective bandwidth higher than 50 Hz and does not need to produce a maximum force output beyond 2.5 lb. Other experiments also showed that increasing the apparent weight or inertia of the structure significantly degrades manual dexterity.

Appendix C expands upon this data by exploring the responses generated by users of a single degree-of-freedom force reflecting device like the one used in the epidural analgesia simulator developed for this project.

Evaluation of Perceptual vs. Physical models for Haptic representations

Appendix C contains a paper which examines the modeling of haptic percepts, comparing the use of perceptual and physical models.

Physical modeling involves developing a mathematical representation based on the physics of the procedure itself. Physical modeling for an epidural simulator involves the development of a mathematical representation of the needle/tissue mechanical interaction with regard to reaction forces. Such a physical model would account for pertinent physical properties of the tissue and even tissue layering. Using this model, the simulator system would derive the reaction force as a function of needle insertion depth or insertion velocity and would reflect that force to the user. In essence, a physical model would represent both the biological tissue and needle and predict the behavior of their interaction.

While it is reasonable to assume that a simulator which can represent the exact physical behavior of the needle/tissue interaction will be perceived by a user as feeling exactly like an epidural needle insertion, it is not necessarily the case that a simulator which almost behaves like a needle/tissue interaction will be perceived as feeling almost real. The information which is missing or distorted may be insignificant from a physical modeling perspective, but may in fact have contained the salient perceptual cues on which a user was relying [Rosenberg 1993]. Since hardware limitations prevent even the state-of-the-art force reflecting systems from perfectly representing physical interactions, it is inevitable that the physical model will not be complete. Since physical modeling provides no indication as to which information is perceptually important to the user, physical

models have the potential to be inefficient or incomplete virtual representations. For example, when generating a haptic simulation of a rigid surface with a physical modeling approach, one might strive to produce an infinite stiffness spring. Since force feedback hardware cannot produce a spring of infinite stiffness, the approach may be to produce as high a stiffness as hardware will allow.

A perceptual analysis of a rigid surface has revealed through human testing that the perception of encountering a rigid surface is not as strongly correlated to stiffness as it correlated to the intensity of the initial jolt [Rosenberg Adelstein 1993, Rosenberg 1994]. The indication being that an adequate perceptual model may be very different from an accurate physical model depending upon the relevant perceptual cues. Thus we can define a perceptual model of a virtual haptic sensation as one which reproduces the salient perceptual properties (i.e. the feel of the interaction) rather than representing the salient physical properties (i.e. the behavior of the interaction). Such an approach generally requires human testing to derive the required perceptual features but it has the potential of resulting in a more efficient and effective virtual representation.

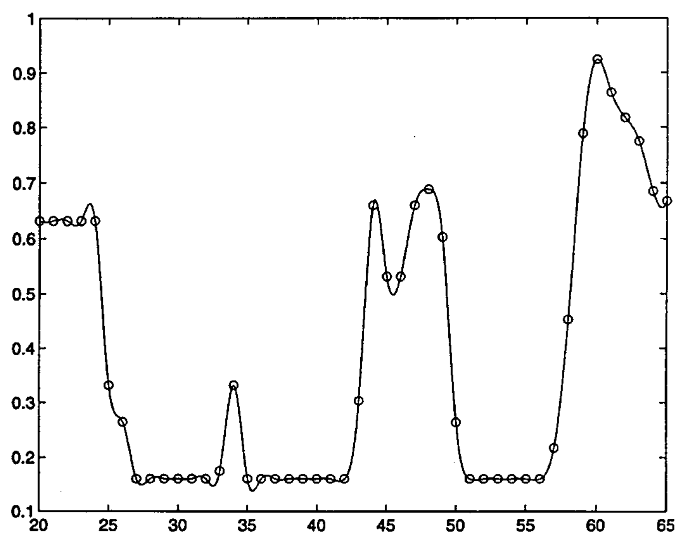


Figure C-6: *CT-Scan Data*

Physical and Perceptual Model Development:

The model represents the virtual tissues; it is responsible for managing the reaction forces generated when the needle passes through the various layers of virtual tissue during the simulated epidural procedure. Two pieces of data closely associated with the epidural analgesia procedure and which are used for training purposes can provide starting points for the development of good models. One of these pieces naturally inspires a physical model and the other a perceptual model. In the following, we shall introduce both but eventually select only one as the superior basis for a model to be used in the product.

A Preliminary Physical Model:

CT-scan or MRI data of the spinal column region is readily available. CT-scans can be

used to produce a volumetric representation which roughly corresponds to tissue water densities. A linear path cut through such a volumetric data set could be used to interactively report the water density of the virtual tissue at the tip of the needle as it traverses the volume under the trainee's control. Quite conceivably, such data could be used to generate the reflection forces. The assumption here, of course, is that water density provides a good direct indicator of the insertion force.

The plot in Figure C-6 shows the density values at incremental locations along the insertion path as collected via CT-SCAN. A spline curve has been fit to the sample data. Tissue layers have also been identified.

We have used this data in an interactive lookup table scheme to implement an epidural simulator. The needle position as it is read in from the encoder is used as an index to the table and the force readout of the table is commanded to the motor. The field generated with this scheme judged by non experts did indeed indicate passage through layers of mechanical properties. The property which varied was easily identifiable as stiffness, in particularly because the force would persist even if the user stopped moving. To index the table not with position but rather with instantaneous would presumably provide a better approximation to the forces reflected from insertion. An important problem, though, is that we do not have a reference or a means of judging the performance of our model without having a person experienced in the epidural procedure to do the testing.

Furthermore, we hypothesize that the water density to insertion force is not so simple and not direct. We assume that a tissue's water density is a simplistic and incorrect parameterization of its mechanical interaction with a needle tip. Other tissues properties such as structure, neighboring tissues, teat strength, and tissue stiffness each of which do not vary directly with water density will certainly play a role in determining needle insertion force. The physical model based on the CT Scan data was a natural first choice and perhaps a good starting point, but we want to point out that the physical parameter it reports is an incomplete picture of the physics we want to find a substitute for.

A Preliminary Perceptual Model:

A practice currently used during the initial training of anesthesiologists provides a plausible starting point for the development of a good model. Anesthesiologists in training start practicing the procedure by inserting the epidural needle through various substitute materials, usually food items. The materials chosen for training purposes are themselves data or sources of data useful for the development of perceptually valid haptic simulation algorithms.

Note that when medical instructors teach this procedure to students they do not describe the feel of the epidural insertion in terms of stiffness and density of tissue structures, but rather describe the process through perceptual analogy. For example, the feel of the needle passing through the skin is often described as puncturing the skin of a tomato. Students are even asked to practice puncturing the skin of a tomato with a needle to familiarize themselves with the haptic percept. Passing the needle through subcutaneous tissue is described as traversing the pulp of a tomato. Penetrating the Supraspinous

ligament feels like penetrating a ripe pear. Hitting the bone is like sticking into a cork board. Although various instructors use various perceptual analogies, the teaching technique is generally to describe the haptic landscape in terms of abstract feel parameters rather than concrete physical parameters.

The Table below lists a perceptual description of the feel of a needle penetrating each region of the insertion path as provided to us by an experienced instructor of this procedure.

TISSUE REGION	PERCEPTUAL REPRESENTATION	FORCE
Skin	"Feels like puncturing the skin of a tomato"	Sudden Increase
Subcutaneous Tissue	"Feels like traversing the pulp of a tomato"	Constant Force
Supraspinus Ligament	"Feels like traversing the meat of a ripe pear"	Increase
Interspinus Ligament	"Feels like traversing the pulp of a tomato"	Decrease
Ligamentum Flavum	"Feels like traversing the meat of a ripe pear"	Sharp Increase
Epidural Space	"Feels like you are exiting a ripe pear"	Sudden Decrease
Bone	"Feels like you hit a cork board with a dart."	Very Sharp Increase

We have characterized the feel of needle insertion into tomatoes and pears using the force and displacement sensored needle. Figure C-7 shows the force readings as a function of needle insertion depth for a layered set of pear and tomato slices. The outer tomato slice had an intact skin in place. The force profile of the pear is visibly different from the force profile of the tomato as seen in Figure C-7. The higher forces in the first 5 mm of tomato are due to the tomato skin.

We have also used this data in lookup table scheme. In order to create the lookup table, the date of Figure C-7 was resampled to a function, filtered, and scaled. Figure C-8 shows a plot of the resulting profile which can now be used as a lookup table.

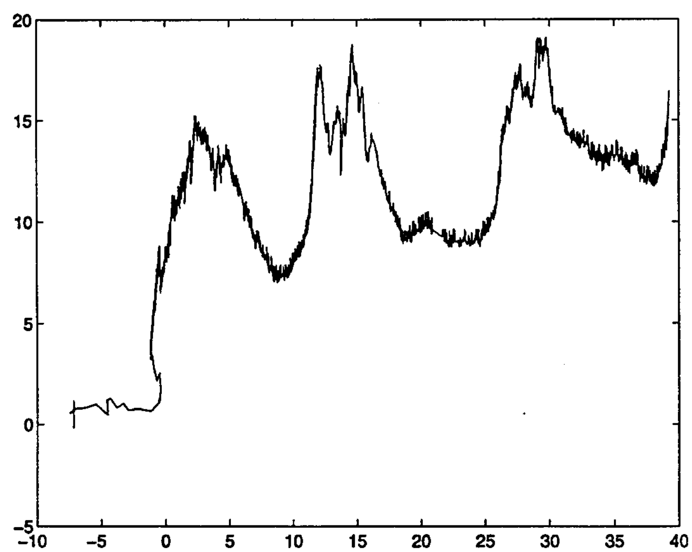


Figure C-7: *Force/displacement Measurements of Real Layered Tomato and Pear Slices*

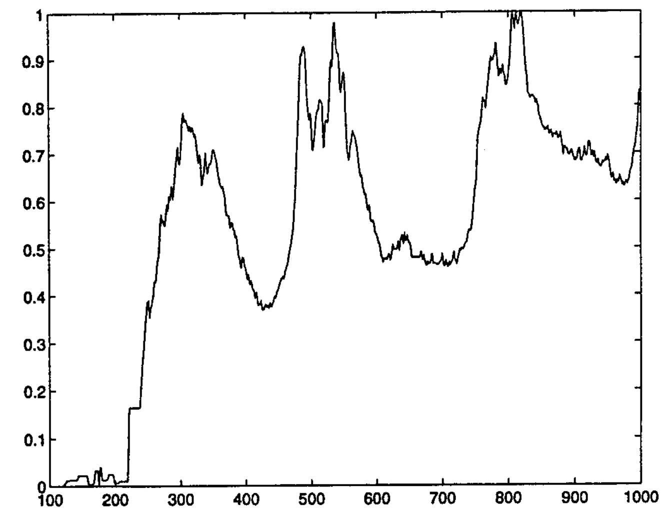


Figure C-8: *Layered Pear and Tomato Profile: Lookup Table for Simulation*

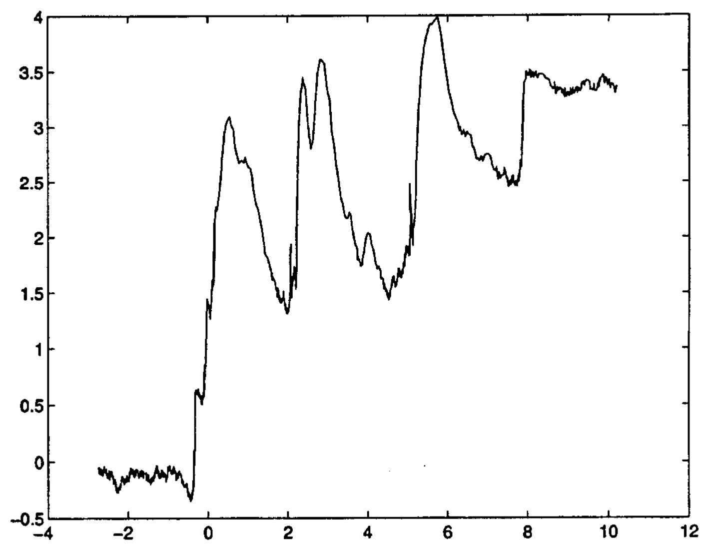


Figure C-9: *Force/displacement Measurement of Virtual Layered Pear and Tomato Slices*

Figure C-9 shows the output force as recorded by the force sensor during a needle insertion through the virtual pear/tomato slices rendered with the lookup table of Figure C-8.

Note first that the forces generated in the simulation, Figure C-9, are scaled down significantly from the forces for generation of the lookup table, Figure C-7. This is due to the particular scaling chosen for the profile, and is not necessary, but does relax requirements on the simulator. The shape of the simulated force profile is indeed very similar to the shape for the lookup table. The motions made by the user during

simulation were similar to the motions made during the recording of Figure C-7, that is, the same insertion velocities were used. Had this not been the case, the virtual and real force profiles would have differed a great deal more. Such is the shortcoming of this lookup table approach. This can only be viewed as a first-cut simulation attempt. Once again, the forces felt were spring forces rather than damping forces since position, not velocity, was used to index the table.

An Enhanced Model

As noted above, the use of table-lookup for the control law is not able to produce a truly interactive simulation. A more complete mechanical model is needed: one that represents the driving-point impedance of the handle during needle interaction with tissue. Input to such a model would include velocity and perhaps acceleration of the handle in the user's grip as well as position. An impedance characterization of the needle/tissue mechanics similar to the kind of modeling of the impedance of the human hand underway at Harvard [Hagian, 1994] would provide models usable for fully interactive simulation. A characterization of the needle's insertion through human tissue will indeed be part of this project. Data will be collected from a cadaver with an instrumented needle by medical instructors. But even before such models are available, we see promise in perceptual modeling. We are building models (control laws) which on the surface appear to be physical models, but which are in fact perceptual models. The basic form contains string and damping terms. But instead of basing the parameter values on tissue characterization experiments, we are selecting them by trial and error with human subjects comparing the virtual feel to the actual feel of needle insertion into pears and tomatoes. A Windows program environment supports real-time adjustment of the feel-governing parameters by the subjects. The experimenter used a dialog box with sliders for run-time parameter to simulate layered materials of varying mechanical properties. Each control law and its associated dialog box has a region of applicability or a pertinent range of insertion depth which can also be edited during run-time. By asking subjects, we can come up with model parameters which minimize the distance between the feel of the virtual and real tissues. Alternatively, the fit parameter could be closeness of the force measurements made during interaction with virtual tissue and sample tissue.

Other aspects of the insertion feel besides its springiness and damping which would be worthy of modeling have been suggested by the heuristic approach. The graininess of the pair, for example, appears to be an extractable perceptual feature. Sharpness of the layer interfaces is another. We are experimenting with various ad-hoc control algorithms aimed at simulating individual features which can be overlaid or added to pre-existing models. We foresee work along the lines of that of Rosenberg and Adelstein [Rosenberg & Adelstein, 1993] which would decompose the perception of the needle/tissue interaction into a number of separable (not necessarily independent) percepts.

Finally, the model can be further enhanced with information available from CT Scan. The model can draw its topology or geometrical description from the CT Scan data yet keep its lumped parameter and overlaid feature form of the perceptual model described above. The variations seen from patient to patient which are available from CT Scan would be a very valuable addition. The tissue would each be identified and their geometrical form

maintained, but the simulation of their interaction would be governed by other models.

Summary:

A number of models have been presented, each of which might form the basis of an epidural analgesia simulator. Data from a force sensor and from the reports of users has been useful for the generation of models and criticism of models. Since our aim is to inspire perceptions in the users of the epidural simulator product, and also because adequate physical models are as yet unavailable, perceptual modeling has come to the fore as the primary model development tool.

An approach which is suggested by these results is one in which MRI data is used to develop tissue topology, this data is matched with a perceptual model of the various tissues, and force feedback is presented based on the perceptual model. This approach and others need to be evaluated in further research.

Evaluation of passive needle insertion simulator

The needle insertion simulator has been evaluated with regard to the amount of energy (work) it is able to dissipate, and most importantly, with regard to the programmability of that amount of work. The needle insertion simulator is a programmable passive device since it is based on a magnetic particle brake. It therefore has only one very specific kind of mechanical impedance in its repertoire: dissipative laws. Two major factors in the performance of the brake and the transmission elements linking it to the needle are of interest: programmability and time response. This write-up addresses only the first of these, programmability. Time response will be important to consider when trying to use modulations on the brake current to produce certain haptic effects. Although not investigated in this study, a nominal time response data point is available in the brake data sheet.

Programmability is further broken down into the following parameters:

Dynamic Range *Repeatability*
Linearity, DAC to force *Inherent Hysteresis*
Constituent Curve: Characterized by a viscous or friction or stiction shape?

Preliminary Observations:

The dynamic range is of course determined by the properties of the brake, under the range of currents provided to it by our interface hardware. Dynamic range can be effectively reduced if the mechanical hardware masks the brake-modulated force with non-programmable dissipative effects. The repeatability will be corrupted by any position or time or side-load dependencies of the needle/user interaction force. Note that histories of position or side-loads may also play a role. We are interested in the relationship between the commanded force (in terms of DAC output) and the actual force. Is it linear? The shape of the force vs. velocity curve will reveal just what kind of dissipative element we are dealing with. Is it at all like viscous damping? (straight line) Is it like friction (side

load dependent-not to be seen in f vs. v plot) or stiction (signum function)? Finally, the force vs. displacement curve will show what kind of hysteretic effects are present. Are they simple backlash or more complex?

The present study investigates the above questions with the hysteresis curve (force vs. displacement) as the focal point and primary tool. The following reasons underlie this decision: Force and displacement are most easily measured on the current device. The area enclosed in the hysteresis loop is a measure of the work done (cumulative work done or energy dissipated in one traversal of the loop). A measure of repeatability of the device can easily be constructed by statistically characterizing the work done in multiple loop traversals.

Procedure

A force sensor (Harvard design, 5-pound Surface Mount Amp with a gain of 1000) was mounted onto the needle insertion simulator in place of the needle handle. A stylus handle was mounted the opposite side of the force sensor to facilitate force/motion input by hand. The 12-bit ADC on the Impulse Engine interface card (see section C.1) was used for force data acquisition. Since the Interface Card ADC accepts 0-10 volts and the force sensor puts out -10 to 10 volts, a simple summing amplifier circuit was constructed on a protoboard to offset the force sensor analog signal. A potentiometer on this circuit allowed for interactive centering of the signal in the range of the ADC and plotting range of interest. After the commencement of testing, this pot was not adjusted so as to not require recalibration. The Immersion postal scale (accurate only to 5 grams) and a set of fishing weights were used to calibrate the force sensor. The serial-port-attached "HCI-3.0" Board was used to acquisition the encoder counts. The stylus handle was manually moved back and forth while the force and displacements were recorded at approximately 100 Hz with the use of a Windows program (docvw3d.ide). Real-time force or encoder vs. time and force vs. encoder reading plots were available during testing from the Windows application. Manual motions were made at approximately 1 Hz through a half-stroke (0.5 in) placed approximately in the center of the displacement range of the simulator. Hitting the endstops during test was avoided. The DAC output was set from the Windows interface at either 0 (low), 2048 (medium), or 4095 (high) and held constant during an entire test. Two additional tests reported at the end of this document (linearity and speed dependence) have procedures which deviate from the above in the following manners: The DAC output was set from 0 to 4000 in increments of 100 for the linearity test. The manual motion varied from approximately .5 Hz to approximately 8 Hz (1 cycle equals one back and forth motion) for the speed dependence test.

DATA ANALYSIS and RESULTS

All collected data was calibrated into units of meters and Newtons with the following straightforward conversions. The throw of the needle was 1.04 inches with 792 encoder counts. See Figure C-10 for the calibration data from force reading to Newtons. Two sets of calibration data were collected approximately 2 hours apart. Both sets are plotted in Figure C-10. Very little drift is apparent from this plot. Note that calibration data was collected for compressive forces only (as was convenient) but was used to calibrate both

compressive and tensile force readings.

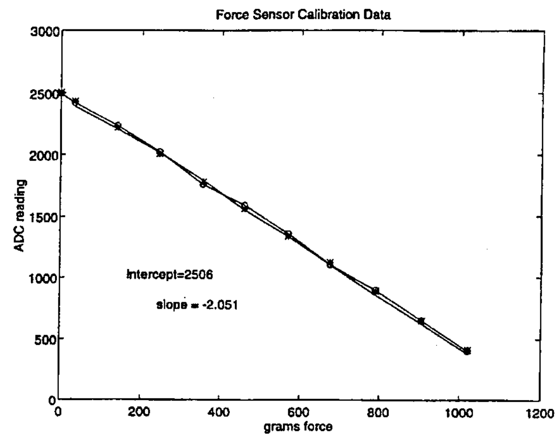


Figure C-10: *Force Calibration Data*

Two designs were characterized: Device 1--The bare aluminum prototype (with poor bushings but low backlash) and Device 2-- the anodized second prototype (with better bushings but bad backlash).

Typical force vs. displacement plots for Device 1 are shown in Figure C-11. Four loop traversals (back and forth motions) each were made with a DAC = 0 setting and with a DAC = 4095 setting. Note that a larger range of motion was executed for the DAC = 0 reading (no reason). Figure C-12. Shows the same plots for Device 2. In comparing Figures C-11 and C-12, one may note that Device 2 (the newer design) has less dynamic range than Device 1. In particular, the DAC = 0 curves have a larger vertical dimension. Unfortunately only three full loop traversals were executed for Device 1 whereas eight were executed for Device 2.

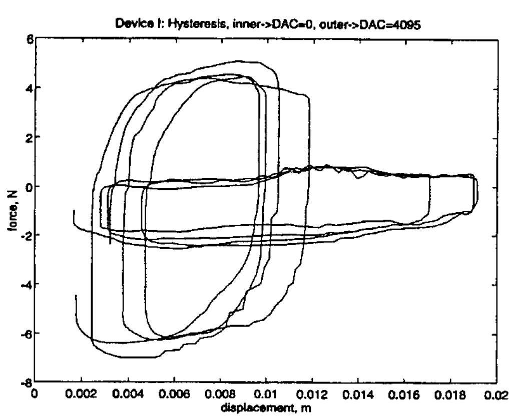


Figure C-11:
Force vs. Displacement Plots
for Device 1: Prototype #1

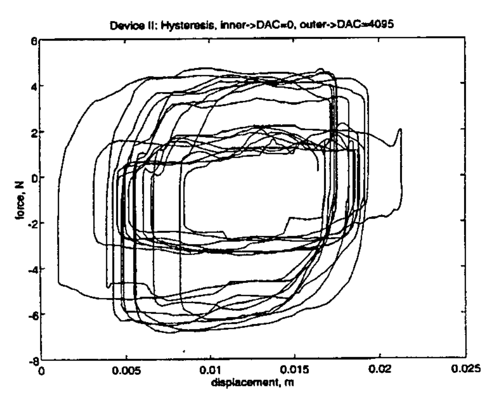


Figure C-12:
Force vs. Displacement Plots
for Device 2: Prototype #2

In order to extract some repeatability measures from the above data, the following data analysis was completed. The zero crossings of the force trace were found with a MATLAB function 'crossup.m'. See Figure C-13 for an example. These were then used as start and stop indices into both the force and displacement traces to chop the plots of Figures C-11 and C-12 into separate loops. Once single loop traversals were in hand, the area enclosed by a loop could be found. That area equals the work done, in units of Newton-meters. The area was found with a simple trapezoidal integration performed on the force vs. displacement data. Figure C-14 shows a typical single loop after extraction. To allay the dependence each of the area data thus extracted, each area was normalized with the range of motion used for that particular loop. The data reported below are therefore in units of Work per meter travel.

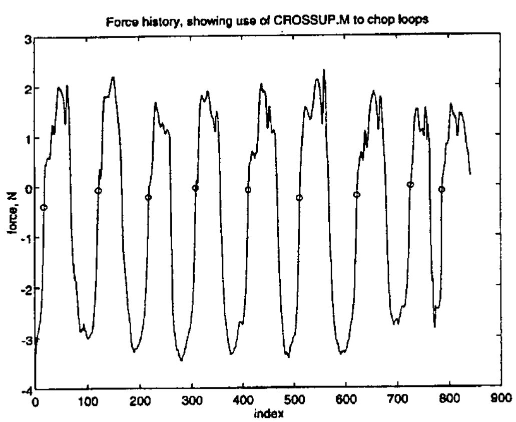


Figure C-13:
Zero Crossings of the Force Trace

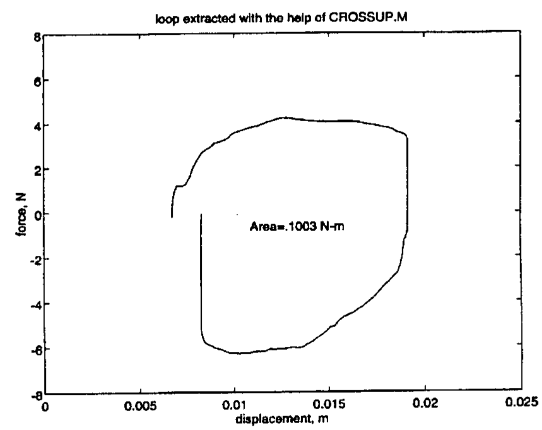


Figure C-14:
Typical Single Loop After Extraction

The sample size (n), mean (x-bar) and standard deviation (sigma) for Device 1 and Device 2 taken at each of three DAC output settings (0-low, 2048-medium, and 4095-high) are as follows:

Device 1

n	2	3	3
x-bar	2.23	5.53	8.62
sigma	.29	.82	.944

Device 2

n	8	8	8
x-bar	2.91	7.76	8.32
sigma	.52	.42	.57

Note that Device 1 does indeed seem to have a larger dynamic range, but Device 2 has better repeatability (though the sample size differences do not allow conclusions about repeatability to be drawn with any confidence).

Figure C-15 shows data used to construct a plot of the Constituent Law for the needle insertion simulator. A range of velocities was produced manually by varying the input frequency of the back and forth motion from about .5 Hz to 8 Hz, as seen in this plot. The velocity signal (top trace) was derived from the encoder signal by first differencing, then filtering. The filtering was done with a Butterworth filter (butter.m) set with a cutoff frequency equal to .6 times the Nyquist Frequency (50 Hz,) that is, 30 Hz. The force vs. velocity trace, or Constituent Law, is shown in Figure C-16. It is not a line. Viscous damping does not describe the brake, as expected. Most striking in this plot, however are the loops appearing at high velocities. These are possibly due to backlash in the coupling from brake to needle handle, though more testing would be needed to verify this fact. Velocity is of course of highest magnitude when traversing the middle of the stroke, not the ends. It would seem that there is a dependence on the change in velocity, that is whether it is slowing down or speeding up, on the part of the force. That is, a dependence on the acceleration! This is certainly plausible. This plot might be showing the effect of the finite mass of the moving parts of the device (including the sprung half of the force sensor). At this time, a full investigation into the causes of this loopy shape have not been undertaken.

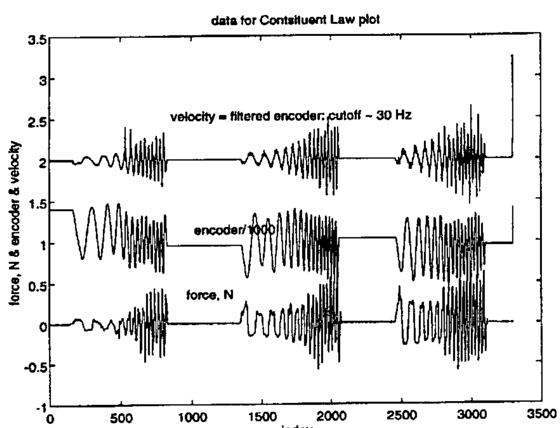


Figure C-15:
Constituent Law Data

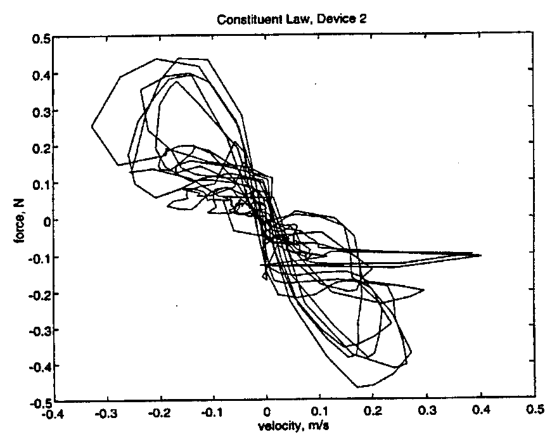


Figure C-16:
Constituent Law

Finally, the linearity of the device (DAC output to force) was checked. The DAC output was incremented in steps of 100 while a consistent back and force motion was input at the needle handle. The force data vs. index is shown in Figure C-17. The timing of the test was such that the index can approximately be read as 100 times the DAC output. This data is not consistent enough to draw any more than rough conclusions from . A more regular motion input is needed which would require a motor under motion (or force) control to produce instead of a human tester.

DISCUSSION

Strictly preliminary conclusions can be drawn based on this data. Repeatability and dynamic range can be improved upon by device design improvements.

Further testing on the time response of the device will be undertaken.

Finally, in order to produce cleaner data and allow more results to be drawn from the data collected, this experiment will be performed again using a motor to actuate the needle. Knowing the mass of the moving parts and the sprung part of the force sensor will allow extraction of the acceleration dependency of the force vs. velocity curve.

Quantification of force feedback requirements from OSC data

The team at OSC has recorded a set of data from an epidural procedure which does indeed extract and display, in quantitative and qualitative detail, a number of haptic cues which arise from the interaction of an epidural needle with a tissue specimen. The data set is most notable for its breadth, that is, its use of multimedia. A time-stamped video recording (with audio track,) was made simultaneously with a computer-mediated recording of force, 6-D position and again, time. The correspondence of certain features in the computer data-file with certain haptic cues can be reliably established by synchronizing the two recordings.

Certain haptic cues which the surgeon noted and verbally identified are almost visually discernible on the video recording. They appear as quick motions of the needle (evidently through harder-to-pierce tissue layers) following brief periods of little or no motion. More valuable for the design of synthetic haptic cues, however, will be the computer-recorded force/position data, so long as features in that data can be clearly extracted and identified as the haptic aspects of certain events in the surgical procedure.

Although still under construction, an overlay of certain animated plots from the computer recordings upon the video recording are most informative. Overlays of the needle-insertion depth versus force plot and the time versus force plots, for example, make evident which features of these plots correspond to which events of the procedure. The axes of the plot are laid out such that the full range in both position and force to be traversed by the plot fit on the video screen. The position-force coordinate pair is graphed on the plot in time-synchrony with the video. That is, a point shows up at the time of recording as a large bold circle, at its proper coordinate position, and moves leaving behind a trail. By the end of the sequence, the full plot is drawn on the screen.

These animated plots are essentially a scientific visualization of what the surgeon felt during the procedure. For example, since forces on the needle are generally compressive during insertion and tensile during extraction, a trace on a plot corresponding to a needle insertion-extraction sequence traverses a counter-clockwise box-like shape. The direction of traversal is counter-clockwise in the present case since insertion is graphed positive to the left and compression is positive toward the top. The first video sequence which records four needle insertion-extraction sequences (the final ending in a puncture into the

epidural space,) is in accordance with an animated traversal of four boxes in the position-force plot. Finer features of the plot (our real interest) quite obviously correspond to force/position events instigated by the surgeon. For example, extra small loops at the far left of the box-shape correspond to probing motions against the relatively hard lamina. Undulations in the force/position graph can be seen to correspond to the stick-slip behavior of the needle during extraction.

Unfortunately force calibration data from these particular recordings was not available, so more than relative force measures can not be determined. However, the relative forces of insertion and extraction are available, as are the force-profiles of finer features such those corresponding to a tissue layer puncture. Fine features which are discernible at this time, before we have actually completed the plot-video overlay, seem to be between 20-50% the size in force amplitude of the full insertion-extraction amplitude.

The data analysis is still underway at this writing, as is the production of a plot-video overlay to be sent back to OSC. The extraction of the needle path from the position and orientation data requires the use of the inverse-kinematics of the probe used for this experiment.

Most importantly, the execution of this preliminary experiment has generated a set of recommendations for the design of the next experiments. Certain issues such as full position and force calibration will be addressed. Special handling of the force-sensored needle by the surgeon so as to not generate ancillary features on the force-position data have been recommended.

For future experiments, we would like to try actual real-time graphing of the force-position plot, overlaid on the video, so that the surgeon, in seeing the force-position features showing up, can perform manipulations with the needle which will emphasize or de-emphasize these features while at the same time reporting verbally the haptic sensations.

Evaluation of Active and Passive Components

In an effort to determine the trade-offs between active and passive technologies to identify the optimal solution for a force feedback device to be used both in this project and in the general purpose haptic interfaces which hopefully will emerge as a result of this effort, we examined data from OSC, as well as their observations as to the applicability of certain types of force feedback to specific surgical procedures. The hardware implementation at OSC revealed a number of these observations, as discussed in the following section.

C.3 Experimental and Development work at OSC

SIMULATION IMPLEMENTATION DETAILS

Voice activation:

Through voice activation, the user may request to view the penetration of the needle and the surrounding regional anatomy. Through voice captured files, the system will prompt the user for which cardinal plane; axial, coronal, or sagittal, is to be displayed. Once the section is displayed, the probe is locked so that the user may not move the needle to a new depth. This limitation has been imposed so that the user does not become dependent on the visual, since these will not be available during actual practice. The intent of presenting the sections is to assist them in building a cognitive map of the regional anatomy and to correlate haptic sensations with structural anatomy.

Initial Mapping of Force Data:

There are two common techniques for the administration of an epidural. One is the median approach, by which the needle is placed between the interspaces of the lumbar spinous processes, and the trajectory of the needle is in the midsagittal plane. The second approach is the paramedian. here the needle is inserted a few centimeters lateral to the midline. For expedience, we chose the median approach to begin development.

Volume data of the regional anatomy of the lower back was obtained by employing a 3-D spoiled gradient echo protocol. This was performed on a General Electric 1.5 Tesla magnet. To capture the radio signals, a custom RF coil placed directly on the surface of the back.

To correlate force data with magnetic resonance data, a generic trajectory for a midline approach was established by visually locating the spinous processes between Lumbar 1 and Lumbar 2 in the magnetic resonance data. 8 bit intensity values were extracted from volumes that were traversed.

A digital referent of the actual needle was synthesized by the computer and its tip was tracked in relation to the volume data. As the needle's position was tracked in relation to the reconstruction, the Z coordinate (depth) was tracked along with the Z-1, Z+1, and Z+2 data points. We then splined the datum referenced by the Z-coordinate of the needles tip as it traversed the probe. Several splines, including Hermite, Bezier, Catmol-Rom, and Beta were applied under expert evaluation. Bsplines were found to present the most natural feel for the resistive forces normally encountered in the midline approach.

Currently, the system is being modified to drive haptic forces directly from the intensity values located within each voxel. We are exploring various algorithms for sampling neighboring volumes, e.g., all immediate volumes surrounding the needle tip in a 2-D plane of trajectory, or a 3-D sampling of all immediate voxels surrounding the needles tip in a cubic space.

The RF coil produced an imaging artifact where the attenuation of the RF signal skews the volume intensity based upon its distance from the coil. Therefore, we notice a higher signal for volumes closer to the location of the coil, and a dissipating signal the further the volume from the RF coil although both volumes are from similar species of tissue, e.g.. muscle, connective tissue. We are looking at two methods to correct for this attenuation.[1,2] Once the MRI data is corrected, we intend to normalize the data sets and run them through a statistical analysis to identify a correlation between the MRI intensity and the resistance felt against the needle at the voxel located at the tip of the needle.

[1] John Haselgrove and Manfred Prammer: "An Algorithm for Compensation of Surface-Coil Images for Sensitivity of the Surface Coil," *Magnetic Resonance Imaging,*4:469-472(1986).

[2] A. Nelson, Y. Kim, R. Haralick, P. Anderson, R. Johnson, and L. DeSoto: "Stereo and Multiplanar Video Display of 3-D Magnetic Resonance Image Data," *Journal of Imaging Technology,*15:74-78(1989).

Rendering of the Back:

To render the back, we begin with a series of CT slices saved in RGB format. We create a volume data set by stacking these slices on top of one another. This volume data set is used as input to the Marching Cubes (Lornsen, W.E. and Cline) algorithm in order to create an iso-surface made of small polygons. The back is then rendered on a Silicon Graphics workstations and the GL programming library.

The Marching Cubes algorithm creates a large number of polygons, which slows down the rendering of the back to below real-time. This can be fixed in a couple of ways:

a) Decimation of the Iso-surface:

Currently no decimation algorithm is implement to reduce the number of polygons. eg, Schroeser, Zarge, and Lorensen in SIGGRAPH, 1992. In the event that head tracking or user viewpoint tracking is required, we will implement this algorithm and tests its efficacy for delivering real-time performance..

b) Storing of the Rendered Image:

The current system supports re-selection of the viewpoint under user control through the mouse interface. As the viewpoint does not need to be updated in real-time, we store an image of the rendered iso-surface and load the image every time we need to redraw the scene. Using this method , we need to re-render and store a new image only if the users viewpoint has changed. However, this has implications when updating the cast shadow.

c) Modifying the Marching Cubes Program:

Currently we are testing a simple way of reducing the number of polygons. It is a simple modification of our marching cubes program. In this modification we make an assumption

that the surface we want is basically smooth, 2D, and takes up most of the volume. With these assumptions we can modify marching cubes to just create one front surface which greatly reduces the number of polygons. A further reduction of polygons could be accomplished by running a decimation algorithm on that front surface.

Rendering of the Needle:

The needle is an iso-surface of polygons created with modeling software. The needles tip can be set any where parallel to the back which allows various insertion points. The needles insertion distance is controlled by any of the Immersion devices. However, visually determining the depth of the needle on a 2D display was often difficult. Two methods of correcting this are .

a) 3D Glasses:

Silicon Graphics supports the use of stereo presentation with LCD shutter glasses, CrystalEyes™, to present each eye a different viewpoint of the objects in the screen. This presents the viewer with the illusion that the screen is in 3-D, allowing the user to better determine the depth of the needle.

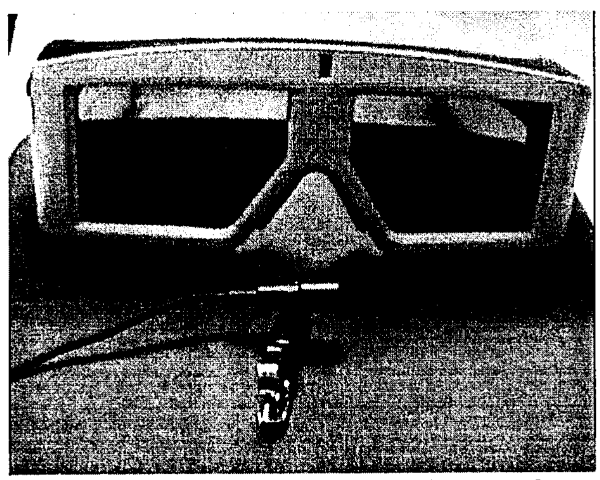


Figure C-17: *CrystalEyes Glasses and Microphone Used*

b) Shadows:

Another method for assisting the user in determining visual depth is the use of the cast shadow of the needle on the back. The cast shadow is created using a method described by Bergeron and creates a shadow volume from the object that is casting the shadow. We have implemented this technique through use of SGI's stencil plane to mask out the pixels in the shadow.

Integration of Immersion Hardware into Simulations

1) The six degree-of-freedom Arm)(Immersion Probe)

When using the 6 degree-of-freedom arm to interface with the simulator, the user is able to

move the graphical representation of the needle around and into the computer-generated reconstruction of the back by physically manipulating the arm. The 6 degree-of-freedom arm does not provide force feedback; the user receives only visual cues to identify the relative position of the needle with respect to the back. These cues include the cast shadow of the needle on the back and perspective, giving the user the perception of depth in the 2D image.

The 6 degree-of-freedom arm can be connected to any SGI workstation via the RS232 port, specifically a 4 processor Power (64 bit) ONYX, a Power Indigo2 Extreme, a Crimson VGXT, an Iris Indigo, and the entry level INDY. Graphics sophistication is determined by the level of graphics hardware available on each machine.

2) One degree of freedom passive force feedback device:

When using the 1 degree-of-freedom passive probe the user receives both visual and haptic feedback from the simulator. The graphics display is identical to the display described above for the 6 degree-of-freedom probe.

The user currently employs the mouse as an interface to select placement of the needle on the reconstructed back. Once positioned, needle penetration is controlled by the 1 degree-of-freedom probe. Intensity values can be obtained from each individual voxel that is penetrated by the tip of the needle. The user can choose to have current intensity values shown, using an intensity meter displayed in a small graphics window.

The passive force feedback system gives the user the feel that the needle is being restricted from movement, which is not realistic. For example, in an actual epidural, as the needle is pressed against the skin the anesthesiologist feels a reaction force pushing back against the needle. This active type of resistance cannot be modeled using the passive force feedback device. This issue is addressed by integration of the 1 degree-of-freedom Impulse Engine described in the next section.

The 1 degree-of-freedom passive probe has been connected to the various SGI machines via the RS232 serial port as mentioned above.

3) One degree-of-freedom Impulse Engine

The 1 degree-of-freedom Impulse Engine has not been connected to the epidural simulation system, because we are unable to interface it with the SGI hardware. This is something that will need to be addressed very early in a Phase II effort to allow us to utilize the simulation power of the SGI workstations. A section has been added below to comment on and suggest solutions for the lack of SGI interface support present in these Phase I prototypes.

We have simulated the Pig Study data and a standard data vector from the MRI data set, using the 1 degree-of-freedom impulse engine connected to the PC via the ISA bus. This simulation hardware gives more realistic force feedback than the 1 degree-of-freedom passive device but does not support any graphics capabilities.

The graphic display is not essential to the task of delivering an epidural. The cognitive task required is that the user must integrate haptic sensations perceived from forces placed upon the needle with mental representations of anatomical structures. The successful integration of the sensory map with a cognitive map is the key to learning proper epidural technique. So at this time, we are able to run limited pilot studies with experts to evaluate the quality of the 1 degree-of-freedom Impulse engine for transmitting lifelike forces encountered in epidural administration. As the connectivity of the advanced probe and more advanced workstations is solved, we will integrate the probe with the advanced graphics workstation and continue summative evaluations.

Experimental Force Study

We currently have a human subjects protocol to obtain structural and force data from cadaver specimens.(Reference same) This protocol is under the auspices of the Ohio State University College of Medicine Willed Body Program. Obviously, obtaining a usable specimen is not in direct control of the researcher.

In order to expedite our sampling of surgical force data, we decided to use an animal specimen for a pilot study. Results of this study have provided useful information which will be implemented in the cadaver studies. The closest anatomical correlate in size was the porcine model. A specimen used for a vascular graft study was obtained from the Lab Animal Resources at The Ohio State University College of Medicine. The animal had been sacrificed within a 60-hour period and was unembalmed. A section of the back, from below the tenth thoracic vertebrae (T10) superiority to the ileal-sacral joint inferiority and 10 centimeters lateral from the midline including the false ribs, was obtained.

The specimen was fixed in a wooden box with surgical tape. No ferrous implements could be used in fixing the specimen because it subsequently was placed in a magnetic resonance imager to obtain structural data (see below). A single degree of freedom force sensor was retrofitted to an epidural needle. The sensored needle was fixed to the Immersion 6 degree-of-freedom Personal Digitizer (see accompanying videotape) using tie-wraps. Spatial coordinates (X,Y,Z) of the needle tip were recorded, along with the roll, pitch, and yaw of the needle, providing the angle of the needle trajectory in relation to the anatomy. Forces transduced by the epidural needle were sampled at 30 Hz. The specimen was spatially registered with vitamin E capsules, which were located by the 6 degree-of-freedom digitizer before administration of the epidural technique. Vitamin E capsules are used; as they are fat soluble, they are resolved by the MRI scanner. They provide registration marks with the structural data from the MRI and the force data.

Two medial approaches and one paramedian approach were performed. The expert vocalized his activities throughout the procedure. The study was videotaped on 3/4" Umatic with a visible time stamp. This video time stamp was registered with the system clock on a 486 PC, which was used to record the force data. Wooden splints were inserted into the wound to register the trajectory of the technique with the MRI data.

Force data was registered by linking the visual time code with the force activity. We then analyzed the force data for significant events by visualizing the 3-D movements of the probe tip and by graphing the function of force vs. time. See figures C-18 and C-19 for this data.

Figure C-18: X Position vs. Time Data

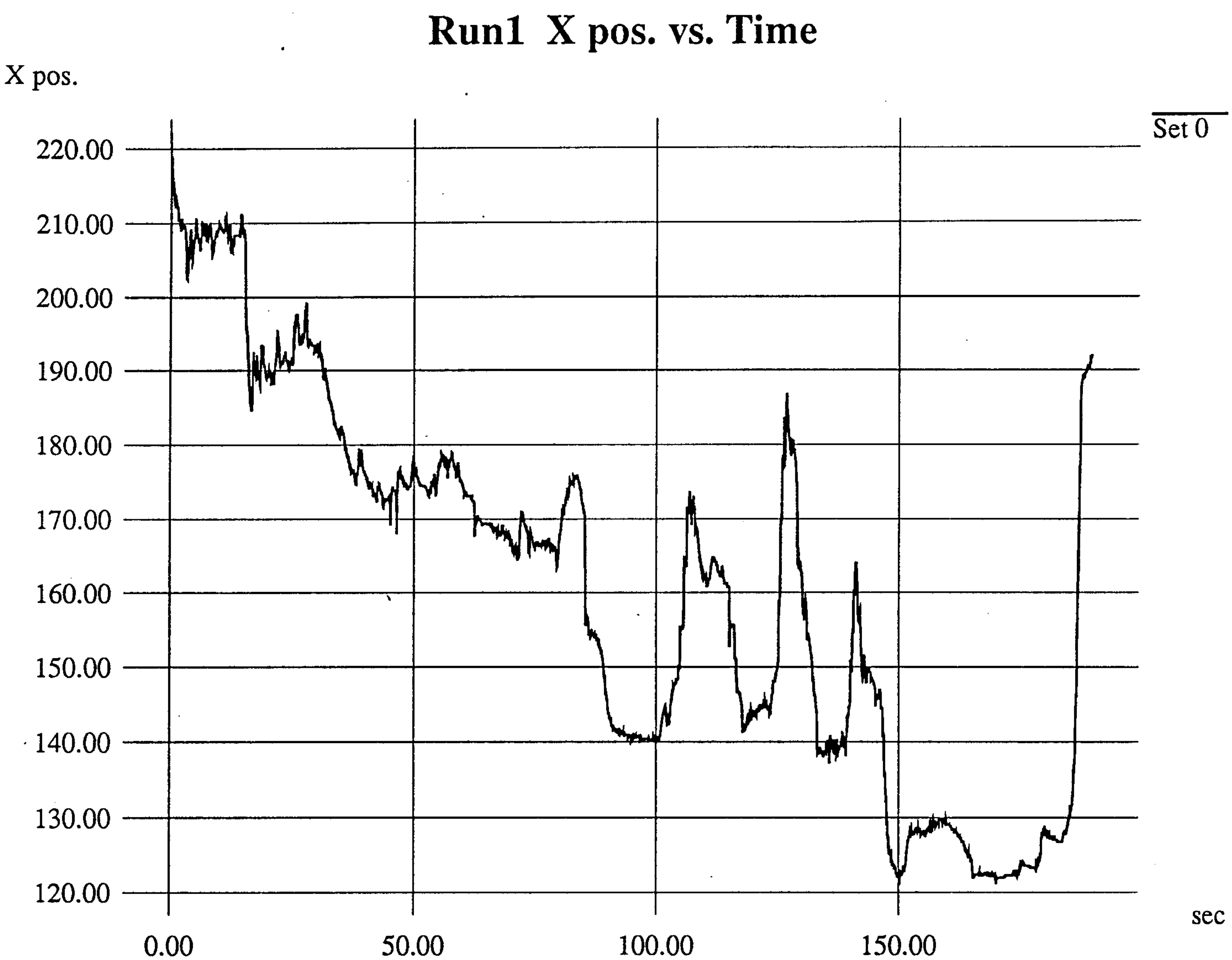
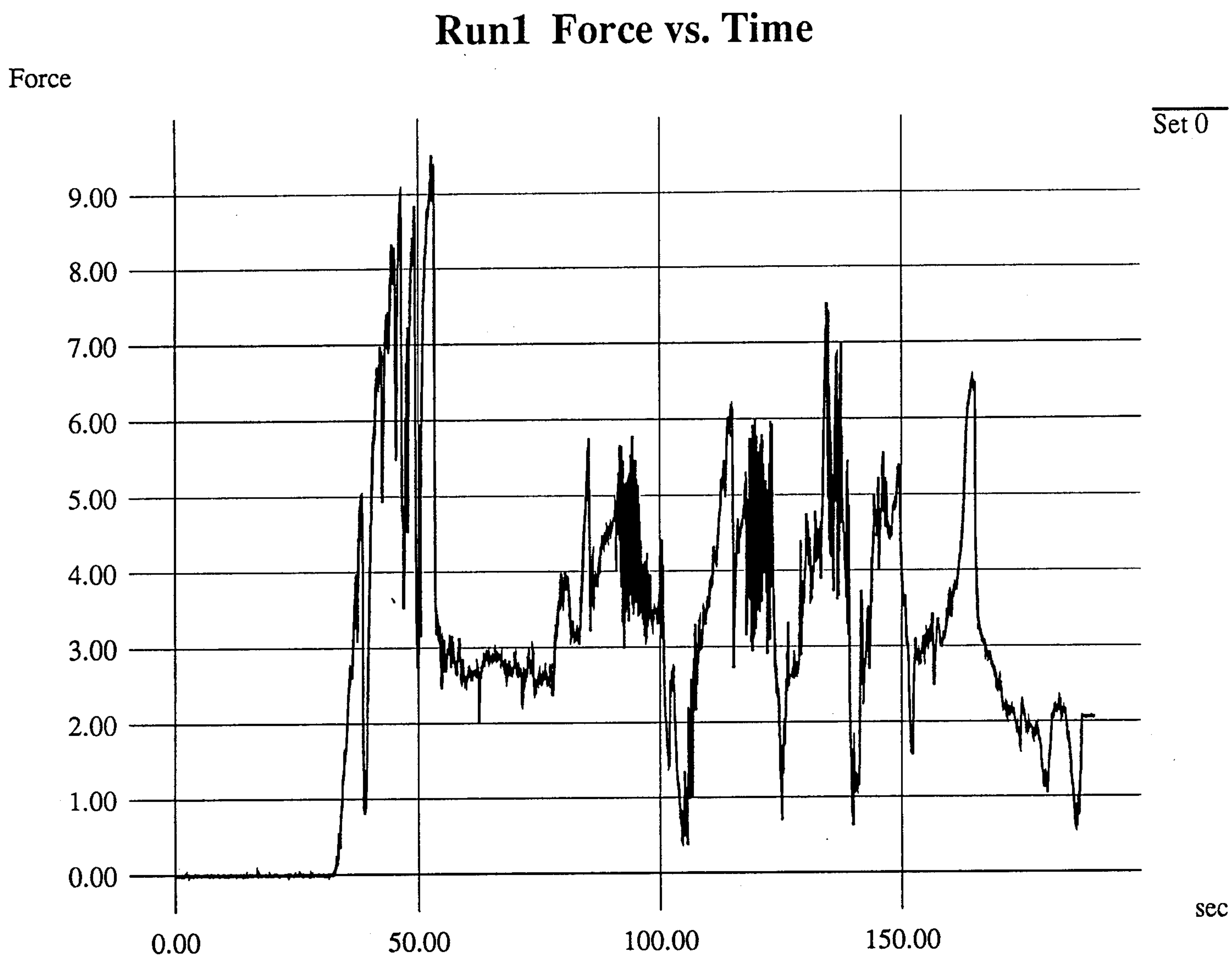


Figure C-19: Force vs. Time Data



Significant areas of the data were rechecked by linking them with the verbal description of the expert and direct visual evidence from the videotape. We then sampled the significant forces involved during penetration of the ligamentum flavum and entrance into the epidural space. This is the critical aspect of learning the epidural procedure - resistance/release. On the one hand the resident must SLOWLY penetrate the resistant tissues of the ligamentum flavum and in addition be prepared to quickly stop all forward movement before penetration into the subarcachnoid space that surrounds the spinal cord.

Figure C-20: *The Porcine Back Section*

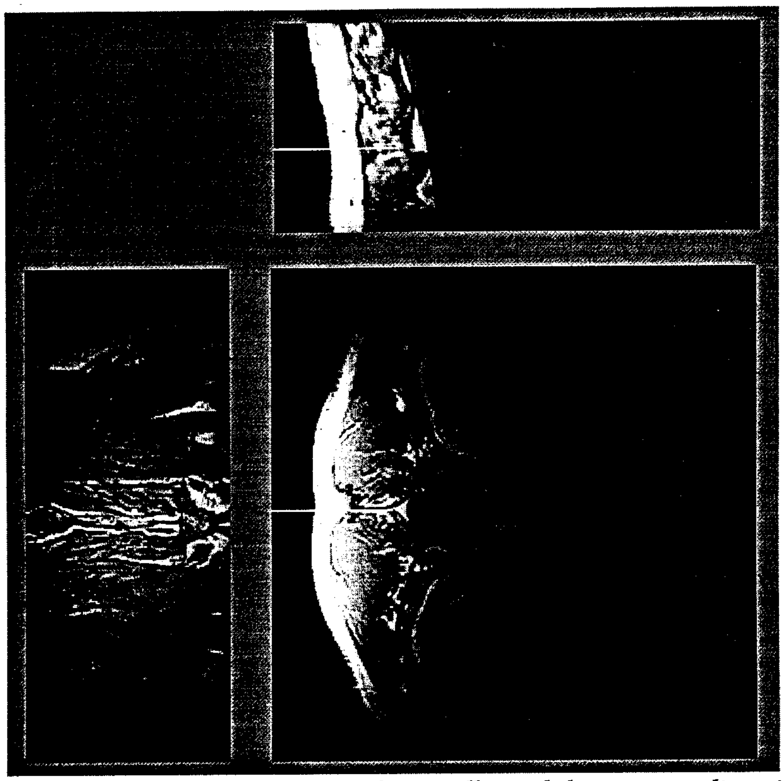


Figure C-21: *MRI Data showing the needle and the surrounding tissue.*

After the force study, structural data was taken from the porcine specimen by placing it a General Electric 1.5 Tesla magnetic resonance imager. A 3-D spoiled gradient sequence, with TR = 30 msec. / TE = 4.6 msec. / Flip Angle of 40 degrees and a Field of View of 24 cm, was employed, providing a submillimeter acquisition with a resolution of 512 x 512 x 124. Scan time was 16:24 minutes. The wound trajectory of needle can be clearly identified in the images.)

Expert Trials with the Device

The data of penetrating ligamentum flavum was placed into a file and used to provide resistive forces to the 1 degree-of-freedom probe. The expert who initially performed the technique on the specimen then provided expert evaluation of the forces played back on the 1 degree-of-freedom probe. The reconstructed force sensation was determined to be significantly accurate to warrant further evaluation by impartial experts.

Subsequently 3 residents with high proficiency levels in technique delivery provided formative evaluation of the force reconstruction. This information provided a more unbiased evaluation, as the initial expert was thoroughly familiar with the study and the equipment. Formative evaluation from these trials concluded that the reconstructed forces provided a familiar sensation to a typical release as experienced when breaching ligamentum flavum.

The limitations were that with the active probe, as the force sensor used on the needle only sampled forces, we needed to simulate the active forces on the needle. This is where we plan to do more tissue modeling of the elasticity and drag features of the penetrated tissues.

Resident Trials with the Device

On June 26th 1995, Three (3) residents from the Department of Anesthesiology at The Ohio State University College of Medicine were asked to assess the two scenarios currently in development for epidural simulation.

PROBE 1:

The first simulation employed the passive-only needle insertion simulator. It was performed on a Silicon Graphics Indigo2 Power Extreme. Graphics of a section of the back were presented to the user. Positioning of the needle referent was mouse driven. An actual needle was used in the haptic probe.

The residents felt that the interface was comfortable to very comfortable to use. One resident commented that the Probe provided a place to "rest and stabilize" their hands during the procedure.

In general they felt the interface was straightforward to use. Most of the comments were centered around a need for additional visual cues for orientation (Note: we did not run the version of the program that runs on the CRIMSON VGXT that supports real-time cast shadows).

Additional comments resulted from the inability to angle the needle. This is a Phase II objective.

As to whether the sensations on this device provided adequate information, the residents reported that it was "too mechanical" and did not provide the differences of tissues or tissue planes. Consequently, they felt this did not provide similar sensations to those encountered in actual practice. A future objective is to present the skin, muscle and facial layers, and penetration of ligamentum flavum.

Modifications that were suggested include:
1. The ability to add degrees of freedom to the needle penetration.
2. Increase the levels of resistive forces.
3. Make the back appear as real as possible with the inclusion of key landmarks for orientation.

PROBE 2:

The second simulation included and active/passive resistance probe. It is a 1 degree-of-freedom impulse engine retrofitted with a epidural needle and a syringe used in technique administration. As the simulation was running on a 486 PC, no graphics were presented.

In general the manual interface was comfortable. However, the residents expressed a desire for a surface to represent the patients back. One resident felt the movements were "stiff". All the residents felt it was straightforward to use. One resident felt the sensations provided adequate information. Two did not.

As to the sensations being similar, they felt it "was very smooth". There was a consensus that the feel "was there" and that with modification, the sensation from the probe would accurately represent the "feel" of the resistive forces encountered while performing the actual technique. However, currently the specific release into the epidural space was too quick and exaggerated. Also the distance traveled by the needle was too great in length.

Of key interest is that the release comes from the syringe, as the fluid is released. In this simulation, the syringe is fixed. This would be a key consideration for Phase II.

Also, it was mentioned that it would be nice to experience patient variance, i.e. obese and/or pregnant patients, pediatric models, the elderly, etc. This is an objective for summative evaluations in Phase II.

Force Feedback Hardware Interface Conclusions and Recommendations

Since the force reflecting hardware to be developed in this effort requires a connection to a high-speed graphics workstation, such as a Silicon Graphics machine, we examined the many options which we could pursue in our commercialization efforts for this technology. We found a number of feasible approaches which we can explore further in a Phase II effort.

1) <u>Connect the force reflecting hardware to the PC, then connect the PC to a SGI</u> machine with a network interface such as Ethernet or RS232. This could be implemented in two ways:

a) The PC would act as an information relay machine forwarding position data from the probe to the SGI and the calculated force data from the SGI to the PC. No force calculations would be performed on the PC. Because of the large amount of data transferred, this implementation would best be done with an Ethernet connection.

b) Use the PC to calculate the forces. To do this, we would pass position data through the PC to the SGI (since the data sets are too large to be stored on the PC). The SGI would, according to the position, send a subset of the data to the PC. The PC would then calculate the forces to be used with the probe. Since the graphics display needs to be updated at roughly 60 Hz, we could connect the PC to the SGI via RS232. This approach would allow us to easily integrate the active feedback probe into our current system after developing a library of routines on the PC like the library used for the passive device.

2) <u>Connect the force feedback hardware to the SGI Indigo2 via its EISA bus.</u> To do this

we would need a printed circuit board, as the board we currently have does not fit. With a card, this solution would be easy to implement, however there could be problems with probe update speed because of the UNIX operating system. Also, this is a single machine solution--- we would still be unable to use the device with the Crimson or the Onyx. This solution would be optimal for the Epidural Simulator.

Human Subject Protocol Summary

Two human subject protocol were obtained form the Biomedical Sciences Review Committee for Research Involving Human Subjects at The Ohio State University. 94H0228, The Investigation of the Use and Efficacy of Advanced and Surgical Computer Interfaces for Biomedical Applications was obtained to study users and advanced interfaces.

Available from FTP site. ftp.osc.edu under /chrm/ftp/incoming/IMM

A second protocol, 94H0415, The Acquisition of Structural and Force Data from Cadaver Specimens for Use in Virtual Surgical Simulations, was obtained to capture high resolution imaging data, and surgical force data.

Available from FTP site. ftp.osc.edu under /chrm/ftp/incoming/IMM

D. Publications and Interactions Related to This Effort

The results of several of the Phase I activities have been submitted for journal publication and for presentation at appropriate conferences.

Appendix C contains the full text of an article submitted by Brent Gillespie entitled "Design of High-Fidelity Haptic Display for One-Dimensional Force Reflection Applications." This paper was published in SPIE Vol. 2351, Telemanipulator and Telepresence Technologies (1994).

Appendix D contains the full text of an article submitted by John S. McDonald, Louis B. Rosenberg, and Donald Stredney entitled "Virtual Reality Applied to Anesthesiology." This paper was published in the Medicine Meets Virtual Reality conference proceedings: *Interactive Technology and the New Paradigm for Healthcare*. K. Morgan, R.M. Satava, H.B. Sieburg, R. Mattheus, and J.P. Christensen (Eds.). IOS Press and Ohmsha, 1995.

Appendix B contains the full text of a abstract submission to the Medicine Meets Virtual Reality #4 conference to be held next January. The submission is entitled "A Virtual Simulation Environment For Learning Regional Anesthesia."

E. Personnel Associated with the Research Effort

Dr. Louis B. Rosenberg received Ph.D., MS., and BS degrees in Mechanical Engineering from Stanford University. Louis Rosenberg is an experienced researcher and path-breaking designer of

immersive human interfaces and virtual reality systems. He has professional experience working in both industry and government laboratories, giving him a broad understanding of the user population. His academic work involved studying the psychophysics of human interaction with virtual environments. His doctoral dissertation focused on the use of force feedback to enhance human performance in manual tasks. This work involved testing human subjects using a 2D force reflecting joystick at the NASA/Ames Research Center. At the USAF Armstrong Laboratories, Louis Rosenberg developed an experimental Master/Slave system for telepresence research using a full upper body force reflecting exoskeleton to display haptic percepts. This involved extensive subject testing to study human performance in a teleoperated tasks with 3-D haptic display. In addition to virtual reality research, Louis Rosenberg has industrial experience designing both mechanical hardware and software products for consumer use. He also has professional experience working at Hewlett Packard and General Motors in the manufacture of both mass produced and limited production parts, giving him deep insight into commercial fabrication processes.

Bernie G. Jackson received an M.S. degree in Electrical Engineering from Stanford University with a focus on adaptive systems theory, audio synthesis and hardware design applications. He is deeply involved in new digital signal processing techniques and physical computing efforts. His talents are on the cutting edge of electrical engineering, and his ability to stay current in the field will allow Immersion to maintain its innovative role in the industry. Mr. Jackson has extensive technical experience in everything from pure mathematics and physical science to applied circuit design and software development. He has developed a VLSI chip for sound synthesis and has written a great deal of software, including an optical character recognition algorithm. He is experienced with most computer systems and is an expert on computer system architecture and interfacing hardware.

Richard B. Gillespie holds a M.S. degree in Mechanical Engineering from Stanford University, and a Bachelor's Degree in Mechanical Engineering from the University of California at Davis. Mr. Gillespie currently works part time for Immersion Corporation while at the same time being a Ph.D. candidate at Stanford University at the Center for Design Research and the Center for Computer Research in Music and Acoustics. Mr. Gillespie's research activities center around the hardware and controller design of haptic interfaces for virtual dynamic systems, especially musical keyboard instruments. He is currently adapting advanced modeling and simulation tools for use in rendering the mechanical impedance of a piano action. User interaction with complex virtual mechanisms, including those with changing kinematic constraints are to be included in the haptic interface/simulator repertoire. Mr. Gillespie is also addressing stability and passivity concerns with analytical treatments of these new controller architectures. Mr. Gillespie has worked four years for Hewlett Packard in the Fiber Optics group. He gained extensive experience in the design and production of plastic injection-molded and insert-molded components. Finite Element Analysis and Statistical Process Control techniques were among his developed specialties. His responsibilities included direct customer interaction and project leadership. Mr. Gillespie also spent six months with IBM designing tooling for the manufacture of data storage devices. He developed user interfaces and robotic hardware/software for various manufacturing processes.

Timothy A. Lacey received an M.S. degree and a B.S. degree in Mechanical Engineering from Stanford University. His double focus included electro-mechanical systems and mechanics of

materials. Mr. Lacey offers an extensive knowledge of the use of materials to develop safe and high-quality products. In addition , his experience designing electro-mechanical systems and software makes him a vital research team member. He is an experienced researcher and has conducted independent work at the NASA/Ames Research Center (as a contractor employed by the San Jose State Foundation), where he developed a new experimental technique for studying crack behavior in welded metal structures containing significant residual stresses. Mr. Lacey is also an associate of the Center for Design Research at Stanford University, where he is working on a collaborative, semi-immersive design environment to enhance conceptual design.

The Ohio Supercomputer Center : Subcontract

Donald Stredney received his B.S. in Medical Illustration and his M.A. in Computer Graphics from Ohio State University. Mr. Stredney is Senior Research Scientist at the Ohio Supercomputer Center in Columbus, Ohio. His work involves the application of high performance computing and advanced interface technology to the field of clinical research and biomedical education. His research interest lies in theories of representation, specifically the applications of computer and volume graphics to the representation of biomedical phenomenon.

His current research includes multimodal studies from electroencephalogram and magnetic resonance images to investigate brain mechanisms of addiction, the use of virtual simulations for assessing user performance is the use of power wheelchairs, and the development of real-time simulators for use in surgical pre-planning and resident education. Specifically, these simulations are being developed for endoscopic sinus surgery, anterior skull and cranial based tumor resection, surgical correction of congenital heart defects, and the simulation of regional anesthetic technique. Mr. Stredney will direct the development of the volumetric data model and the graphical interface of the epidural simulation, and will serve as liaison between the clinical educational research and the engineering of the haptic display.

Dr. John McDonald received his B.A and M.D. from the State University of Iowa. He completed residencies in the Department of Obstetrics and Gynecology , University of Iowa, and in the Department of Anesthesiology at the University of Washington, Seattle. Dr. McDonald is Professor and Chair of the Department of Anesthesiology and Professor in the Department of Obstetrics and Gynecology, at the Ohio State University Medical Center. He is also Director of the Department of Anesthesiology's Pain Clinic. Dr. McDonald founded the acute pain service at The Ohio State University Hospitals in 1986. He is known internationally for his research in acute and chronic pain in both humans and animals. His research includes the study of spinal opiod receptors and anti-nociceptive interactions between opiates and regional anesthetic agents.

Dr. McDonald is uniquely qualified as a domain expert, to serve as evaluator in the modeling of resistive forces, and to oversee the overall clinical applications of the project as well as direct the resident study.

Consultants:

Dr. Bernard D. Adelstein received his Ph.D. from MIT with a thesis on the design of a high-performance two-degree-of-freedom haptic display. Since that time he has been the chairman or co-chairman of many key conferences on Haptic display and has published many papers on the

subject. He currently works for Western Aerospace Laboratories and is a contracted researcher for NASA Ames Research Center, Human Factors and Virtual Reality Lab. His close proximity to our facility will allow us to meet with him and discuss our designs and obtain feedback.

Bruce M. Schena has 11 years of experience in the design, engineering, and control of robotic mechanisms and electromechanical products. He has a BSME ('86) and MSME ('87) from MIT and is currently pursuing a Degree of Engineer in Product Design at Stanford University. He has a comprehensive knowledge of robotics, precision machine design, embedded control, electronics, firmware development, ergonomics, and production engineering. He has published 8 technical and conference papers in the areas of design and robotics and has a number of patents pending. His present thesis work is entitled "Design and Development of a Multiple Node Telepresence System."

F. Relevant Research

Immersion Corporation has done extensive work in the area of manual interaction with 3-D virtual environments. The key Immersion personnel involved on this project have had extensive experience in the area of haptic display for virtual environments. The following is a list published research in the area of haptic display and virtual reality which has been performed by the Principal Investigator, other Immersion Corporation Personnel, as well as the acting consultants on this project.

B. D. Adelstein. (1989). *A Virtual Environment System for the Study of Human Arm Tremor*. Ph.D. dissertation, Department of Mechanical Engineering, MIT, Cambridge MA.

B. D. Adelstein., and Rosen, M.J. (1991). A high performance two degree-of-freedom kinesthetic interface. *Human-Machine Interfaces for Teleoperators and Virtual Environments*, NASA Conference Publication 10071, pp. 108-113.

B. D. Adelstein., and Rosen, M.J. (1992). Design and implementation of a force reflecting manipulator for manual control research. In *Advances in Robotics*, ed. H. Kazerooni, Amer. Soc. Mech. Engr, New York, pp. 1-12.

R. B. Gillespie, *Interactive Dynamics with Haptic Display.* Proceedings, ASME Winter Annual Meeting on Haptic, 1993.

R. B. Gillespie, *Dynamical Modeling of the Grand Piano Action*, International Computer Music Conference Proceedings, San Jose Ca 1992.

L. B. Rosenberg, *Virtual Fixtures aid Telerobotic Control.* Proceedings AAAI Spring Symposium, Towards Physical Interaction and Manipulation. 1994.

L. B. Rosenberg *Design of a Virtual rigid Surface: Haptic / Audio Registration.* Proceedings CHI 94. Boston, 1994.

L. B. Rosenberg, *The Perceptual Design of Virtual Haptic Sensations*. Proceedings Virtual Reality Systems Exhibition 1993.

L. B. Rosenberg, B. D. Adelstein. *The Perceptual Decomposition of Virtual Haptic Surfaces* Proceedings IEEE Research Frontiers in Virtual Reality 1993.

L. B. Rosenberg. *Virtual Fixtures: Perceptual Tools for Telerobotic Manipulation.* Proceedings IEEE Virtual Reality Annual International Symposium, 1993

L. B. Rosenberg. *The Use of Virtual Fixtures to Enhance Teleoperator Performance in Remote Environments with Time Delay.* Proceedings, ASME Winter Annual Meeting on Haptic Interfaces for Virtual Environments and Teleoperator Systems, New Orleans, Louisiana 1993

L. B. Rosenberg. *The Use of Virtual Fixtures As Perceptual Overlays to Enhance Operator Performance in Remote Environments.* Technical Report AL-TR-1992-XXX, USAF Armstrong Laboratory, Wright-Patterson AFB OH, 1992. In publication.

L. B. Rosenberg, "*The Use of Virtual Fixtures to Enhance Operator Performance in Remote Environments*" SPIE Telemanipulator Technology, 1993.

L. B. Rosenberg. *Perceptual Design of a Virtual Rigid Surface Contact*. Technical Report AL-TR-1993-XXX, USAF Armstrong Laboratory, Wright-Patterson AFB OH, 1992. In publication.

The Ohio Supercomputer Center is involved in several projects that are related to Virtual Reality and/or the use of 3-D volumetric models. Most of this work involves the volume reconstruction of CT or MRI acquired data and multi-modal imaging and the exploration of these data sets through parallel implementation on high-performance computing.

- Poly Drug Abuse: EEG and Behavior. This research is funded by the National Institute on Drug Abuse and is in collaboration with the Neuropsychopharmacology Laboratory at McLean Hospital of Harvard Medical School. This work involves the integration of P300 evoked potentials with magnetic resonance images to identify dipole sources in the human brain. The goal of this research is to better understand the mechanisms of the human brain during drug addiction.

- Accessing Diagnostic Accuracy of Virtual Simulations of Brain and Cranial Base Tumors. This is an interdisciplinary effort to integrate current surgical practice in tumor management with new and evolving interface and high performance computing technology.

- The Determination of Environmental Accessibility and Wheelchair User Proficiency through Virtual Simulation. This research is funded by the National Institute on Disability and Rehabilitation Research and is a sub-project of the Ohio State University Rehabilitation Engineering Center. Through computer pre-visualization, architectural designs are examined for ADA compliance. In addition, the virtual system is used to assess the user's performance in using a power chair.

- Visualization of the Heart Through three-dimensional reconstruction of Magnetic Resonance Images. This research is funded by Children's Hospital Research Foundation, Columbus, Ohio. The work involves the in-vivo acquisition of human heart data for use in pre-surgical planning studies that involve the surgical correction of congenital heart defects.

In addition to the experiences of our Principal Investigator, our team includes two consultants who are highly experienced in the fields of force feedback, dynamics, and human motor control. Dr. Bernard Adelstein and Brent Gillespie are both well known researchers in the field of haptic display and have produced many relevant publications including:

Adelstein, B.D., *A Virtual Environment System for the Study of Human Arm Tremor.* Ph.D. dissertation, Dept. of Mech. Eng., MIT., Cambridge MA, 1989.

Adelstein, B.D., and Rosen, M.J. *A high performance two degree-of-freedom kinesthetic interface.* "Human-Machine Interfaces for Teleoperators and Virtual Environments", NASA Conference Publication 10071, pp. 108-113, 1991.

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Gillespie, R.B.. *The virtual piano action: design and implementation*, International Computer Music Conference (ICMC) Proceedings, Held: Aahus, Denmark, Oct. 14-18, 1992. pp. 447-448.

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The following references provide background information and related research on computer based medical simulation, visualization techniques, and surgical procedures.

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Udupa, J.K. and D. Odhner, "Interactive Surgical Planning: High-Speed Object Rendition and Manipulation Without Specialized Hardware", in Proceedings of the First Conference on Visualization in Biomedical Computing, pp. 330-335, May 1990.

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Yagel, R. and W. Ray, "Visibility Computation for Efficient Walkthrough Complex Environments", accepted to PRESENCE, April 1994.

Yagel, R., D.S. Ebert, J. Scott, and Y. Kurzion "Grouping Volume Renderers for Enhanced Visualization in Computational Fluid Dynamics", accepted to IEEE Transactions on Visualization and Computer Graphics, Vol. 1, No. 2, July 1995.

Ying, K., P.Schmalbrock, BD Clymer, Echo-time reduction for submillimeter resolution imaging with a phase encode time reduced acquisition method, Magn. Reson. Med. 33, 82-87, 1995

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Fundamentals of MRI, Editors: Donald W Chakeres, Petra Schmalbrock, Williams and Wilkin, Baltimore 1991. S Kurucay, P Schmalbrock, A Segmented Interleaved, Motion and Inhomogeneity Compensated FISP Sequence, Annual Meeting of the Society for Magnetic Resonance, Nice 1995

G. Relationship with Phase II R & D

From Phase I, we have a high-performance single degree-of-freedom haptic interface employed in an effective medical simulation with force feedback. We have experimental results which quantify the usefulness of this haptic display technology in a real-world medical training application. We also have a strong technical foundation to apply to the full 3-D haptic interface system in Phase II.

Phase II objectives will consist of developing a complete working prototype of a six-degree-of-freedom stylus-based haptic display interface system. This will require designing and building the mechanism to size, weight, inertia, and resistance specifications determined in Phase I. This will also include incorporating sensor and force feedback hardware that meets the bandwidth, resolution, and resistance specifications derived in Phase I. The Phase II effort will also involve refining and completing the control electronics, interface electronics, and software drivers to complete the 3-D system. The final part of Phase II will involve developing sample software applications which demonstrate the merits of the haptic interface system. Ohio Supercomputer Center will extend the medical simulation system developed in Phase I into 3-D and take advantage of the full six-degree-of-freedom haptic display developed in Phase II. At the end of the Phase II contract period, we hope to have a commercially viable haptic simulation platform for 3-D medical applications. This would have direct implications to general surgical and microsurgical techniques, including telesurgery or telerobotics. Future research would include model deformation to the visuals. This would provide additional perceptual congruency to the resistive forces being reflected to the user.

H. Commercial Applications Potential and Technical Feasibility

H.1 Wide Range of Interdisciplinary Potential

Commercial potential for a force-reflecting user interface is very broad-based. Given that most commercial user-computer interfaces employ a "point-and-click" approach with a standard "mouse," it is clear that physical manipulations are becoming more and more a part of practical computing in all professional fields. No matter what an on-screen image represents, the ability to manipulate it *and feel it* simultaneously can only add to the user's power to quickly perceive and control what the computer is doing. The relatively low cost of the proposed approach to force reflection makes commercialization feasible in many different fields.

Applications range from desktop file management to advanced applications such as scientific analysis or computer-aided design. Analysts examining multi-dimensional models can display information using haptic characteristics to represent parameters (springiness, inertia, etc.). Without force feedback, analysts can interactively explore a data set only to the extent that it can be displayed visually, perhaps as a multi-axis graph or color-coded contour model. By using force feedback, the analyst can display additional data that would have cluttered the visual domain or would have been otherwise impossible to incorporate in an intuitive fashion.

H.2 Federal Government/Military Potential

The proposed manual interface with force feedback will be a tremendously powerful and portable tool for many tasks undertaken by the federal government. Beyond the uses mentioned above, a force-reflecting interface is immediately useful wherever virtual reality or immersive environments are employed. The Haptic Display would be ideal for making virtual training procedures more realistic by adding physical feel to the sensory domain. The device would be important for navigation through computer-generated landscapes or maps: the implementation of force feedback could allow navigation and surveillance to be performed by feel as well as by sight. The device could also be used for telemanipulation, where force feedback has been shown to enhance operator performance. For example, haptic feedback could be used to enhance performance in remote repairs or in the telerobotic cleanups of hazardous materials.

H.3 Anticipated Benefits and Immediate Commercial Niche

Presently, there are no commercial products for haptic display on the consumer market. A few small firms do manufacture very expensive force reflecting interfaces to serve the research community, but those products are not cost effective for any real world applications. By implementing the innovative hybrid haptic display technology, Immersion Corporation expects to produce a commercial haptic interface which is not only cheaper to produce than traditional mechanisms for force feedback, but is also inherently safer than typical force reflection technologies, due to its passive components. As a result, end users have been unable to take advantage of force reflection in real world applications.

Our goal is to develop a commercial product which is in a comparable price range with other computer peripherals such as monitors, printers, and data storage devices. Such a product would empower computer users to interact with computational information in the same way that they interact with information in the real world, using their natural perceptual facilities to analyze and interpret the display.

Of the many potential applications of Force Feedback technologies, Immersion Corporation plans to focus on two primary markets: Engineering and Medical Simulation. These are markets which Immersion Corporation currently targets with existing products. Because of our current presence in these markets, name recognition and technical reputation will allow Immersion Corporation to quickly and effectively introduce force feedback technologies. The following paragraphs discuss the potential benefits which force feedback can bring to a number of industries.

Medical Virtual Reality: Surgical Training

The initial commercial target will be virtual simulations for medical training. Adding Force Feedback to Virtual Reality simulations can greatly increase the physical realism, and thus enhance the overall effectiveness of the application. Within a virtual environment which employs force-feedback technologies, users can interact with and explore computer simulations by making use of their natural sensory and motor skills. Users of such systems can obtain an intimate level of insight and understanding of computational models not provided by traditional simulation techniques. Because force feedback adds physical realism to simulation environments, force-

feedback technologies have an enormous potential in the training and planning of manual tasks.

One the most exciting applications of force-feedback simulation technologies is surgical simulation. Computer environments which realistically replicate the LOOK and FEEL of medical procedures could be used as teaching tools, allowing manual procedures to be learned in computer labs rather than using cadavers or laboratory animals. Imagine a Virtual Reality medical simulation system so realistic that users actually feel the physical properties of the tissues and organs they interact with. The simulation could replicate the feel of inserting a needle into human tissue, the feel of making an incision with a scalpel blade, or even the feel of removing a gall bladder with a Laparoscopic Instrument.

The idea of human tissue simulation will not only benefit the physician, but all of the allied health care providers, such as nurses, physical therapists, and anyone directly involved with patient care. The more realistic the virtual model is, the more likely the transfer to actual practice. This translates into less patient morbidity. Individuals with more experience are less likely to have difficulty with performing a procedure. We all want the nurse with many years of experience to start the intravenous line in us, not the student who may be performing the procedure for the first time on a real patient.

The *Virtual Epidural Simulator* developed in Phase I will be one such application which will serve a very important niche in the field of medical education. Currently, there are 75 departments of anesthesiology associated with accredited medical schools, and an equal number of satellite teaching units are affiliated with medical centers. At the present time there is no effective way to train doctors on the epidural procedure without putting live patients at risk, and therefore these organizations are practically a captive audience for a force-feedback system. It is foreseeable that a new method for teaching regional anesthesia techniques safely and inexpensively could greatly improve this aspect of medical education and thereby improve the quality of health care delivery.

The system allows physicians the freedom to experiment with new techniques in a non-threatening environment. Also, with the advent and proliferation of endoscopic techniques in other areas of medicine and surgery, the basic tools will be in place to simulate heretofore undeveloped techniques. Lastly, the concept of being able to monitor actual physical technique will allow for more adequate testing of novice surgeon proficiency. As the proposed system can be set up as a master/slave environment, expert faculty can "feel" the forces that a novice is utilizing, or conversely, the novice can "experience" the delicate forces that an expert utilizes to perform a specific technique.

Engineering: CAD/CAM and Simulation

Imagine a Computer Aided Design system which not only allows designers to visualize mechanical parts under development, but actually provides realistic force feedback so that users can FEEL the physical properties of structures still on the drawing board. Long before concept drawings were fabricated into physical prototypes, the designer could feel the weight, inertia, compliance, even texture of the parts being developed. This application clearly has the potential to speed the design process. These technologies will give the designer an intuitive understanding of the components under construction which numbers and drawings alone can not provide.

APPENDIX A: Design Specifications Document

In a force feedback human interface system, the flow of information forms a closed loop, as shown below in Figure AA-1. The user can be seen as the starting and ending point in this loop. The cycle begins when a user makes a gesture or physical motion within the simulated environment. Sensors track the user's physical motions and relay this information to the system's governing computer. The computer then uses dynamic algorithms to calculate the haptic sensations that the user should feel as a result of the physical motion as well the defined contents and structure of the simulated environment. Haptic sensations are then produced by driving a set of actuators. The actuators produce real physical forces which make their way to the user's body through a mechanical transmission. When the user perceives these synthesized forces and reacts to them, the cycle is complete.

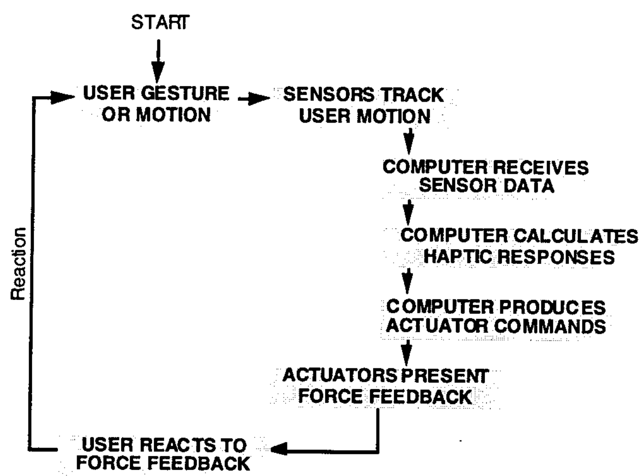

Figure AA-1, Force Feedback System Flow of Information

The fundamental goal when designing a force feedback system is to allow the user to perform natural gestures and interactions within the simulated space and create feedback forces that feel realistic and convincing. A system which achieves such a situation is described as having high fidelity. The fidelity of a force feedback system depends on each component in the cycle described above. If any single component is insufficient, the realism of the simulated environment may be significantly corrupted.

The system's overall performance is summarized by its *bandwidth*, which is a measure of the highest frequency of motion that can travel all the way through the system. Haptic sensations that feel "sharp" or "crisp" require high bandwidth, whereas those that are more gradual, or "mushy" sensations, do not require high bandwidth. The system's overall bandwidth can only be as good as the bandwidths of it sensors, actuators, and mechanical transmission -- frequencies that are attenuated at any one component will not be able to travel through the entire system.

The fidelity of a force feedback system therefore depends on:

a) the accuracy and precision of the sensors
b) the processing speed of the central computer
c) the performance of the actuators

d) the transparency of the mechanical transmission.

a) Sensor Performance

A sensor is primarily characterized by its resolution, accuracy, and speed. A sensor's resolution is defined as the smallest possible increment between any two different measurements. The sensor resolution needs to be adequate for the computer to detect the smallest motions that constitute significant user activity. For digital sensors, such as optical encoders, the resolution is simply the difference between adjacent quantized readings. For analog sensors, such as potentiometers, the resolution is more subtle and depends on statistical properties of the output signal as well as the density of the eventual quantization. Acceptable sensor resolution is a parameter governed primarily by the properties of the human perceptual system. With insufficient resolution, users will perceive disconcerting vibrations and discontinuities. When designing a haptic interface, it is crucial to maintain a sensor resolution such that the haptic signals in the desired output frequency range are well represented.

Accuracy specifies how true a given reading is. The sensor accuracy must be sufficient to ensure that a worst-case error between the sensor reading and the true value does not cause unacceptable errors in haptic output, when propagated through the system. If a sensor's inaccuracy is well-characterized, then it can often be compensated for by the governing computer, although such compensations can become a computational burden and slow the system. For human in-the-loop systems, absolute sensor accuracy is usually not as important a design parameter as net sensor resolution. This is because the human perceptual system is much more sensitive to relative changes, or differentials, than it is to absolute magnitudes.

A sensor's speed determines how quickly its output will respond to the user's motion. Any lag due to the sensor will simply add to the lag of the entire system, degrading its bandwidth, and preventing the production of "crisp" sensations, such as contact with a rigid surface. Thus it is desirable to use sensors with as little internal lag as possible. This often makes digital sensors, such as optical encoders, preferable to analog sensors, such as potentiometers, which are typically slower and require a time consuming analog to digital conversion process.

b) Computation and Communication Latency

Once the user's motions have been detected by the sensors, there are several sources of delay. It takes time for the sensors to transmit their data to the governing computer and for the computer to calculate what output forces are required based on the given simulation. It also takes time for the computer to send the resulting force commands to the actuators.

While the processing delay is a function of the simulation complexity and the processing speed of the host computer, the transmission delay is a function of the communication method and protocol. One popular method for computer peripherals is RS-232, or serial communication. This is one of the more widely-supported communications standards across various computing platforms, but it is often too slow for haptic display. In systems with a small number of sensors and actuators, it may be possible to achieve acceptably low latency with RS-232, especially if a

clever data-encoding scheme is used. However, for systems in which a high volume of data is flowing, parallel interfaces such as SCSI or direct motherboard interface may be necessary. The system could also contain a host processor and a fast interface such as Ethernet, which could communicate with any existing computer system equipped with Ethernet.

Our ISA card solution presented in Attachment C provides direct access to sensor information for immediate position input and direct access to digital-to-analog converters for immediate commanding of force signals. The direct access is provided by placing all the interface components onto the PC bus, removing any time delays from communication with an external device. This solution is not as attractive from the compatibility point of view, but new bus standards such as PCI may allow us to produce a commercially feasible product which works with many existing computing platforms without customization.

c) Actuator Performance

Actuators are characterized primarily by their maximum force output and response time. The response time, as with the sensors' response time, will add to the system's overall lag and degrade system bandwidth. The maximum force must be sufficient so that when fed through the mechanical transmission it can represent the desired range of forces for the given simulation. Such magnitude requirements are highly dependent upon the task at hand.

Requirements for high actuator force output can put significant demands on the design of the mechanical transmission. Typically, an actuator with high output capability must be larger and heavier than one with low output capability. High-output actuators also typically require more power and can complicate output circuitry. In addition, a high-output actuator can be potentially dangerous if it imparts large forces to a user's hand or body. For these reasons, the haptic display system should be designed with as small a maximum force output as is acceptable to represent the given simulation.

d) Transparency of transmission

The transmission which lies between the actuators and the user should introduce as few dynamic effects as possible to the overall system. An ideal transmission would not alter the actuators' output in any way, and the user would perceive the desired forces exactly. Any real transmission, however, is characterized by stiffness, mass, friction, backlash, and backdrivability, all of which can degrade the force relayed to the user. Unfortunately, it is nearly impossible to achieve the ideal case in all of these areas. Instead, any design must make trade-offs for the resulting system to have sufficient bandwidth for the required task. Luckily, the human perceptual system is highly forgiving and can tolerate significant non-idealities in the transmission without degrading the perceptual effect. The key to designing an effective and efficient haptic interface is to make use of human perceptual limitations to reduce the mechanical design requirements. The following subsections address the key transmission parameters.

STIFFNESS. It is desirable that the transmission between the actuators and the user is highly rigid, with minimal compliance. Compliance in the transmission would reduce the system's

mechanical bandwidth and limit the representable frequency content of haptic information. Therefore, compliant transmission members such as belts and cables should be avoided or sized sufficiently stiff for the dynamic range of forces to be produced. If cable drive systems are used, the cables should be pre-loaded by a tensioning mechanism.

MASS. To maximize the output efficiency of a haptic interface, it is desirable to have minimal inherent inertia in the interface mechanism between the actuators and the user. As a result, less actuator effort would be wasted to accelerate the mechanism's mass, leaving more force to be applied to the user. Reduced inertia will also increase the mechanical bandwidth of the system and increase the representable frequency range.

FRICTION & DAMPING. To maximize the output force capabilities of a haptic interface mechanism, it is desirable to dissipate as little energy as possible to inherent friction and damping. Also, for precise control of force output, it is desirable to minimize non-linearities imposed by rubbing friction or viscous damping. Minimizing friction and damping also helps to ensure backdrivability. Thus, a primary design consideration for a 3D haptic interface is minimal inherent friction and damping. This implies employing precision bearing surfaces and high quality joints and avoiding using gears and other transmission components. A published technique to improve bandwidth (Colgate, 1993) in active (motorized) systems is to add damping to the physical system and then compensate for it in the control law.

BACKLASH. Backlash in the transmission between actuators and the user can corrupt the feel of the haptic information produced at the interface. Thus backlash-prone transmission components such as gears, chain drives, and lead screws must be avoided in hardware design. Backlash-free alternatives which should be used include direct drive, cable drive, belt drive, or rigid link drive.

BACKDRIVABILITY. A fundamental requirement of a force feedback computer interface is its ability to allow the user's hand to apply force and move the mechanism while at the same time allowing the mechanism to apply force and move the user's hand. In other words, the mechanical transmission which links the user's hand to the actuators must be completely backdrivable. The result is a system in which a user can apply delicate forces and be met with minimal opposition from the mechanism unless the computer deliberately induces resistance forces. Backdrivability is a fundamental design parameter which excludes common mechanical transmission elements such as gears and lead screws from consideration. Highly backdrivable transmission alternatives include direct drive, cable drive, belt drive, or rigid link drive.

Appendix B: Abstract submitted to MMVR4 Conference

A VIRTUAL SIMULATION ENVIRONMENT FOR LEARNING REGIONAL ANESTHESIA

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Overview

The College of Medicine of The Ohio State University, Immersion Corporation, and the Ohio Supercomputer Center have developed a virtual simulation environment to teach the complex technique of epidural placement. This methodology was presented at Medicine Meets Virtual Reality in January, 1995. Since that time, we have developed a working beta model to test actual residents in anesthesiology residency programs in the United States. The system provides an intuitive interface for manipulating virtual data sets that are three-dimensional volume reconstructions of actual patients. The model is flexible, has excellent adaptability, does not wear out, and provides a fresh form of learning a technique that, in the human model, presents a threatening environment and difficult learning curve.

Administering an epidural block to a patient is a technique that a resident approaches with great improper administration leads to inadequate pain relief for the patient or worse, the delivery of the technique actually causes pain. We are initiating trials of the virtual simulation with residents who have previously learned on the human model as a comparison. We have developed a method for learning that is not threatening and that facilitates multiple practice events without supervision. Currently, the system is undergoing evaluation for its efficacy to raise resident proficiency levels for actual human placement of an epidural and its ability to maximize transfer to actual technique delivery.

Volumetric data acquisition employs a submillimeter acquisition pulse sequence that provides a 512 X 512 X 124 resolution data set resulting in a 64 Megabyte file. This data set is culled for visible surfaces and rendered on a high performance graphics workstation. A visual referent of the needle used in the technique is displayed over the representation of the volumetric data of the patient. The user places an actual needle into a force reflecting probe. The position of the actual needle is correlated to the digital referent, and force data is calculated, based upon the tissues which have been penetrated. The forces are driven back to the haptic probe and presented to the user.

At any time, the user may request, through a discrete phrase recognition interface, a cardinal section of the placement of the needle and the regional anatomy. During graphic presentation of the sectional view, the haptic probe is locked, preventing the user from depending on the visual; as this cue would not be present during the actual technique.

We will present our methodologies for obtaining force data during actual technique delivery, subsequent data analysis, and resulting use of information in force modeling. In addition, we will present our methods to correlate force modeling with tissue densities obtained from the magnetic resonance data.

We will present results from trials run with anesthesiology residents. These trials employ formative evaluation using a think-aloud protocol by which the user verbalizes actions and mental decisions continuously throughout the trial. System evaluation and iterative design will employ written evaluation tools..

Appendix C: SPIE Publication

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Design of High-Fidelity Haptic Display for One-Dimensional Force Reflection Applications

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Design of High-Fidelity Haptic Display for One-Dimensional Force Reflection Applications

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ABSTRACT

This paper discusses the development of a virtual reality platform for the simulation of medical procedures which involve needle insertion into human tissue. The paper's focus will be the hardware and software requirements for haptic display of a particular medical procedure known as Epidural Analgesia. To perform this delicate manual procedure, an anesthesiologist must carefully guide a needle through various layers of tissue using only haptic cues for guidance. A simplifying aspect for the simulator design, all motions and forces involved in the task occur along a fixed line once insertion begins. To create a haptic representation of this procedure, we have explored both physical modeling and perceptual modeling techniques. A preliminary physical model was built based on CT-scan data of the operative site. A preliminary perceptual model was built based on current training techniques for the procedure provided by a skilled instructor. We compare and contrast these two modeling methods and discuss the implications of each. We select and defend the perceptual model as a superior approach for the epidural analgesia simulator.

Introduction

Several research labs and small companies around the country are currently involved in projects aimed at generating hardware and software to teach medical procedures through realistic computer simulation..[1,8] Human interface products which track the activities associated with certain medical procedures and provide for interaction with computerized tissue and organ models are already appearing on the market. A Laparoscopic Surgery Simulator from Immersion Corp. is an example of one such product. This tool allows a user to wield surgical tool handles and perform the manual manipulations associated with laparoscopic and endoscopic surgery. Simulators which can also provide haptic feedback to the user yet which meet low cost requirements are likewise under development. Sometimes called force reflecting interfaces, these simulators allow for interaction between user and

model which include power exchanges, timed and governed to enhance not visual, but mechanical realism. A Catheter Insertion Simulator from Immersion Corp. falls into this category. This devices allows a user to insert a catheter wire into a virtual patient while the computer tracks the wire's feed and spin. In addition to monitoring manipulations, the computer can command a resistance force to the wire to simulate the forces generated when a catheter interacts with body tissue. The result is a human interface platform capable of providing a realistic representation of the manual task and which can be used for training medical professionals.

A product currently under development is the Virtual Epidural Simulator which is a single degree of freedom force reflecting interface designed specifically to provide users with realistic simulation of the medical procedure known as Epidural Analgesia. In addition to the physical hardware for haptic display, this project also requires the development of software techniques for generating the haptic representation of a needle passing through layers of tissue. After briefly introducing the hardware design, this paper will address the fabrication of models for simulating the haptic aspects of the epidural procedure. We will pay particular attention to the need to balance engineering and psychophysical considerations in the design of these models. Two approaches to the process of building models will be highlighted. We call the two approaches physical modeling and perceptual modeling. Running commentary will be provided on each presented model as to whether it fits into the physical or perceptual model paradigm.

We hope that to emphasize the modeling process in the presentation of these models will prove useful. Although certainly we don't expect to be able to come up with directives about which modeling approach is appropriate at any given time, we do hope to spur the development of further design tools by elucidating the various approaches to the process of model construction. After presenting some further background, this paper will introduce the preliminary hardware design, discuss the generation of some design parameters, present a physical and then a perceptual model, and finally discuss future model development efforts before summarizing.

Background

Epidural analgesia is one of the most frequently used techniques for the prevention of pain during surgery. The procedure involves the injection of a local anesthetic or an opiod into the epidural space of the spinal column. Once inserted, the needle does not change direction, its motion is constrained to a line by the dense ligaments. Nevertheless, it is a delicate manual operation. The anesthesiologist must insert a catheter into the epidural space using only haptic cues for guidance. As the needle passes through various tissue layers, a varying insertion force is detectable by feel. By constantly comparing this feel to a mental map of the anatomy and an associated map of expected feel, it is possible to a maneuver the needle into the correct space without damaging the spinal chord. All practitioners of the epidural process must possess this detailed mental map of the needle/tissue mechanical interaction with its associated haptic cues at the needle handle. No visual cues are available since the needle's path is hidden below the surface of the skin.

While epidural analgesia is a common procedure with wide-spread clinical use, current techniques for training students to perform this procedure can be difficult for both student and instructor. The problem is that there is no effective way for students to develop the required mental model of the haptic landscape without practicing the manual insertion on actual live patients. This creates a dangerous situation for patients, a stressful learning environment for the student, and a teaching process which requires instructors to spend much time performing interactive supervision. What is needed is an off-line simulation environment in which students can repeatedly practice the procedure and develop the manual skill without endangering patients and without requiring constant instructor supervision. To meet this need, Immersion Corp., in collaboration with researchers at Ohio Supercomputer Center and Ohio State University Medical Center, is working on a realistic virtual simulation of the epidural procedure. This DOD funded project focuses on developing hardware and software which can reproduce the haptic sensations associated with epidural needle insertion so realistically that it can be used as an effective teaching tool.

The proposed system, known as the Virtual Epidural Simulator, would include a force-reflecting interface which generates the appropriate haptic cues associated with needle penetration of the various layers of biological tissue. It will provide a trainee with a believable, non-threatening environment which encourages the free exploration of the many variances confronted in administering a lumbar epidural. Such interaction and exploration with a simulator should increase the resident's understanding of the anatomy and the intricacies encountered in the epidural procedure. It is hypothesized that such a training environment will reduce resident anxiety and limit the number of trials required to learn to successfully deliver regional anesthesia through the epidural method.

Hardware Description

The hardware for this project is made up of two parts: Haptic Sensing Hardware and Haptic Feedback Hardware. Basically, force and position sensing hardware is needed to devise models to be used in the position sensing and force producing feedback hardware.

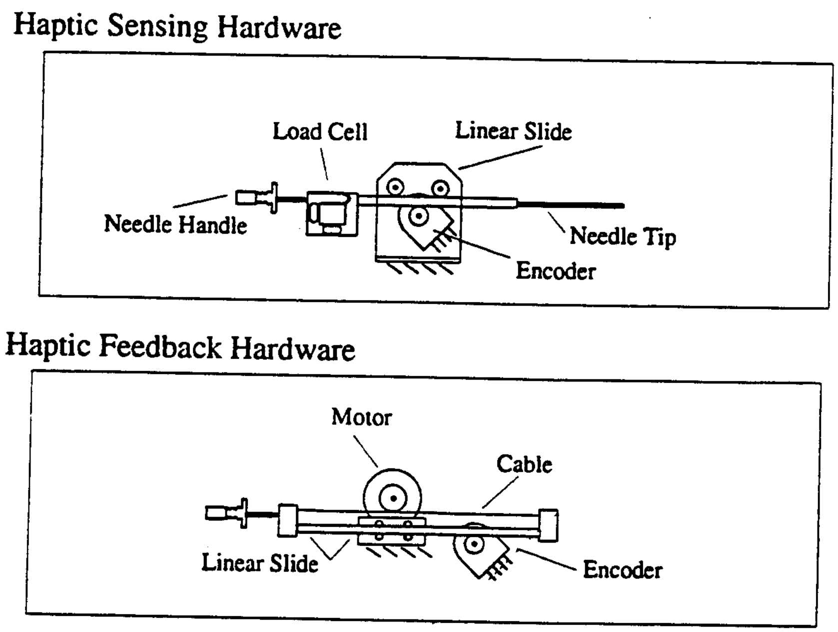

Figure 1: *Hardware*

Figure 1 shows both the haptic sensing hardware and haptic feedback hardware. The haptic sensing hardware is essentially an instrumented epidural needle. The epidural needle has been mounted on an extra long light-weight handle which is constrained to linear motion without twist by a set of high quality bearings. A small strain gage outfitted load cell which has been electro-discharge machined out of aluminum comprises the force sensor. The amplification circuitry is located right on the load cell on a surface mount printed circuit board. An in-house design 16-bit A/D converter and a low-cost digital IO card allow for acquisition of the force signal by a 486DX2-66 PC. Finally, a 1024 count/revolution rotary encoder with a friction drive wheel on the needle handle is responsible for transducing the position of the needle.

The hardware for the haptic feedback product is made up of a linear slide motorized through a capstan drive by a low-inertia precision motor. A highly flexible steel cable takes three turns around a screw pulley on the motor. For simplicity and low cost, we have decided not to include a force sensor in the final product.

Therefore, measured force will not be available for use in a control law or table lookup scheme. An encoder is again responsible for tracking position of the slide. To minimize inertia, the rod itself moves and the platform is fixed.

The haptic sensing and feedback hardware is used in three configurations. The sensing hardware is used alone with tissue substitue samples to generate simulation models. The sensing hardware is then used together with the feedback hardware to test candidate models. Finally the feedback hardware alone will constitute the simulator.

C++ code for Windows on the PC is responsible for closing the control loop and supporting a full graphical user interface for development and product use. Eventually, the system will include a graphics workstation for the visual presentation of a virtual needle and CT-scan images.

Design Parameter Generation

Already the hardware has proven itself inadequte. It has become apparent that the mass of the force sensor on the needle masks a significant portion of the feel of inserting a needle into a pear. See the Perceptual Model section below for a discussion of the importance of the pear. Quick experiments with naive subjects showed that the ability to differentiate a pear from a tomato was degraded by the presence of the force sensor on the needle. Since the stiffness of the force sensor is very high, its mass must be culprit in the masking effect observed. A simple lumped-parameter mass spring model of the needle in the grip of a trainee has been used to show that indeed the mass of the force sensor must be smaller in the next design. Figure 2 shows some experimental data taken to characterize the stiffness of a typical needle handle grip. The measured force is plotted against measured displacement. The slope of a line fit to the data estimates the stiffness at 15,000 N/m. Note that more information such as damping is also available from this data, but a simplistic model is deemed sufficient for the present purposes. This stiffness value used in two mass-spring models, one with and one without the mass of the force sensor gives two approximate cutoff frequencies. The addition of the 28 gram force sensor to the 3 gram needle would then account for the lowering of a cutoff from 2200 Hz down to 700 Hz.

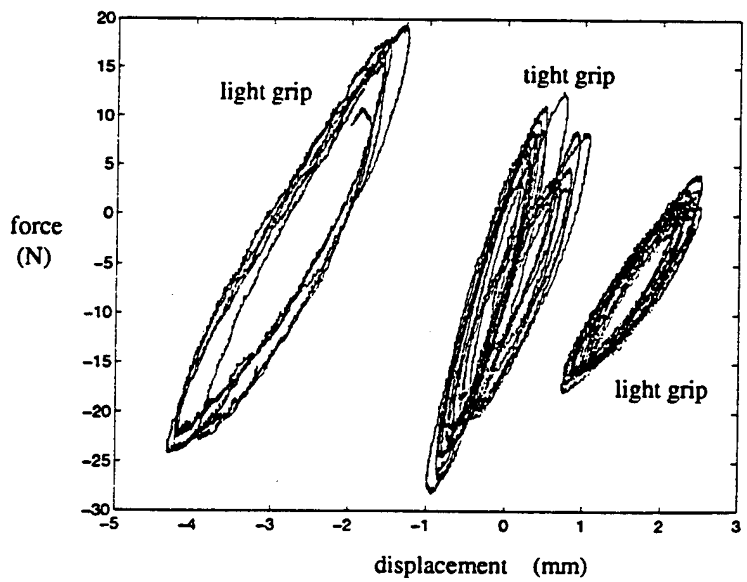

Figure 2: *Grip Stiffness Characterization*

We are not ready to conclude that vibration frequencies in the 700-1000 Hz range could account for the masking effect observed, but this ballpark analysis does suggest that the presence of the force sensor could be attenuating valuable frequency information within the range of human haptic sensitivity. Further experiments

with an accelerometer are underway to come up with solid design parameters for a suitable design of the haptic sensing hardware.

Certainly the force feedback hardware introduced above will not have a frequency production capability above 50 Hz. In order to produce such frequencies for haptic display, we are proposing the use of a vibrotactile display such as that developed by Howe and Kontarinis.[4,5] A small 'proof mass' actuated by a tiny voice coil motor could be driven with a waveform containing the high-frequency information.

Physical vs. perceptual modeling

When trying to replicate the forces generated when a needle passes through the various layers of tissue during an epidural procedure, there are several possible approaches one can pursue. The model or control law which will govern the force generated for the user to feel will take on one of a few forms. It may be implemented as a lookup table, an equation, or even as a differential equation within a numerical integration scheme.[2] In the following sections of this paper, we will present several preliminary models which we have used to date to re-create the feel of the epidural procedure.

Two basic approaches are available for generating the model: physical modeling and perceptual modeling. Whether a model is physically or perceptually based is somewhat independent of its form. For example, an equation can be a physical model or a perceptual model depending on how it was derived. The physical/perceptual distinction can also be used to judge a model independent of its derivation: does it accurately predict behavior (physics) or adequately inspire interpretation (percept)?

Physical modeling involves developing a mathematical representation based on the physics of the procedure itself. Physical modeling for an epidural simulator involves the development of a mathematical representation of the needle/tissue mechanical interaction with regard to reaction forces. Such a physical model would account for pertinent physical properties of the tissue and even tissue layering. Using this model, the simulator would derive the reaction force as a function of needle insertion depth or insertion velocity and would reflect that force to the user. In essence, a physical model would represent both the tissue and needle and predict the behavior of their interaction.

While it is reasonable to assume that a simulator which can represent the *exact* physical behavior of the needle/tissue interaction will be perceived by a user as feeling *exactly* like an epidural needle insertion, it is not necessarily the case that a simulator which *almost* behaves like a needle/tissue interaction will be perceived as feeling *almost* real. The information which is missing or distorted may be insignificant from a physical modeling perspective, but may in fact have contained the salient perceptual cues upon which a user was relying.[7] Since hardware limitations prevent even state-of-the-art force reflecting systems from perfectly representing physical interactions, it is inevitable that the physical model will not be complete. Since physical modeling provides no indication as to which information is perceptually important to the user, physical models have the potential to be inefficient or incomplete virtual representations. For example, when generating a haptic simulation of a rigid surface with a physical modeling approach, one might strive to produce an infinite stiffness spring. Since force feedback hardware cannot produce a spring of infinite stiffness, the approach may be to produce as high a stiffness as hardware will allow. A perceptual analysis of a rigid surface has revealed through human testing that the perception of encountering a rigid surface is not as strongly correlated to stiffness as it is correlated to the intensity of the initial jolt.[6,9] The indication being that an adequate perceptual model may be very different from an adequate physical model depending upon the relevant perceptual cues. Thus we can define a perceptual model of a virtual haptic sensation as one which reproduces the salient perceptual properties (i.e. the feel of the interaction) rather than representing the salient physical properties (i.e. the behavior of the interaction). Such an approach generally requires human testing to derive the required perceptual features but it has the potential of resulting in a more efficient and effective virtual representation.

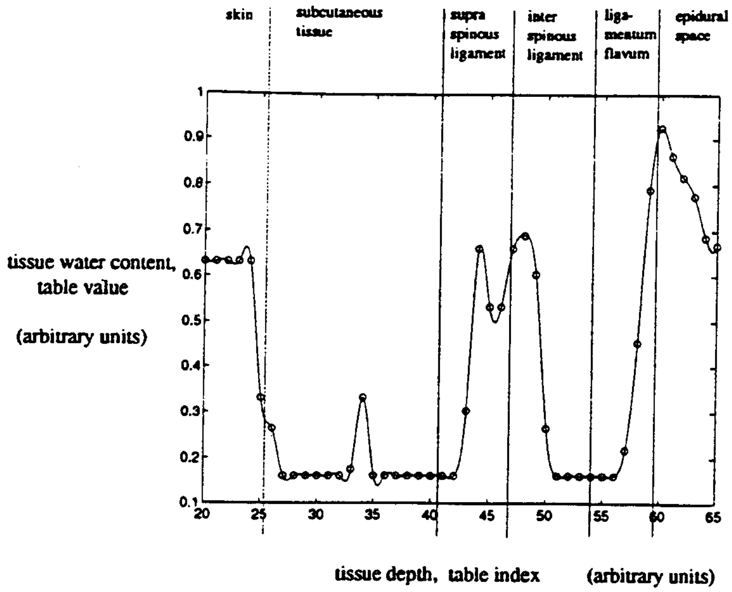

Figure 3: *CT-scan data*

Model Development

The model represents the virtual tissues; it is responsible for managing the reaction forces generated when the needle passes through the various layers of virtual tissue during the simulated epidural procedure. Two pieces of data closely associated with the epidural analgesia procedure and which are used for training purposes can provide starting points for the development of good models. One of these pieces naturally inspires a physical model and the other a perceptual model. In the following, we shall introduce both but eventually select only one as the superior basis for the model to be used in the product.

A preliminary physical model

CT-scan or MRI data of the spinal column region is readily available. CT-scans can be used to produce a volumetric representation which roughly corresponds to tissue water densities. A linear path cut through such a volumetric data set could be used to interactively report the water density of the tissue at the tip of a virtual needle as it traverses the volume under the trainee's control. Quite conceivably, such data could be used to generate the reflection forces. The assumption here, of course, is that water density provides a good direct indicator of the insertion force.

The plot in Figure 3 shows the density values at incremental locations along the insertion path as collected via CT-SCAN. A spline curve has been fit to the sampled data. Tissue layers have also been identified.

We have used this data in an interactive lookup table scheme to implement an epidural simulator. The needle position as it is read in from the encoder is used as an index to the table and the force read out of the table is commanded to the motor. The feel generated with this scheme judged by nonexperts did indeed indicate passage through layers of varying mecahnical properties. The property which varied was easily identifiable as stiffness, in particular because the force would persist even if the user stopped moving. To index the table not with position but rather with instantaneous velocity would presumably provide a better approximation to the forces reflected from insertion. An important problem, though, is that we do not have a reference or means of judging the performance of our model without a having person experienced in the epidural procedure to do the testing.

Furthermore, we hypothesize that the water density to insertion force relationship is not so simple and not direct. We assume that a tissue's water density is a simplistic and incorrect parameterization of its mechanical interaction with a needle tip. Other tissue properties such as structure, neighboring tissues, tear strength, and tissue stiffness each of which do not vary directly with water density will certainly play a role in determining needle insertion force. The physical model based on the CT-scan data was a natural first choice and perhaps a good starting point, but we want to point out that the physical parameter it reports is an incomplete picture of the physics we want to find a substitute for.

A preliminary perceptual model

A practice currently used during the initial training of anesthesiologists provides a plausible starting point for the development of a good model. Anesthesiologists in training start practicing the procedure by inserting the epidural needle through various substitute materials, usually food items. The materials chosen for training purposes are themselves data or sources of data useful for the development of perceptually valid haptic simulation algorithms.

Note that when medical instructors teach this procedure to students they do not describe the feel of the epidural insertion in terms of stiffness and density of tissue structures, but rather describe the process through perceptual analogy. For example, the feel of the needle passing through the skin is often described as puncturing the skin of a tomato. Students are even asked to practice puncturing the skin of a tomato with a needle to familiarize themselves with the haptic percept. Passing the needle through subcutaneous tissue is described as traversing the pulp of a tomato. Penetrating the supraspinous ligament feels like penetrating a ripe pear. Hitting the bone is like sticking into a cork board. Although various instructors use various perceptual analogies, the teaching technique is generally to describe the haptic landscape in terms of abstract feel parameters rather than concrete physical parameters.

The Table below lists a perceptual description of the feel of a needle penetrating each region of the insertion path as provided to us by an experienced instructor of this procedure.

Insertion through:	Feels like:
skin	puncturing the skin of a tomato
subcutaneous	traversing the pulp of a tomato
supraspinous ligamet	traversing meat of ripe pear
interspinous ligament	traversing pulp of tomato
ligamentum flavum	traversing meat of ripe pear
epidural space	exiting ripe pear
bone	hitting a cork board with a dart

We have characterized the feel of needle insertion into tomatoes and pears using the force and displacement sensored needle. Figure 4 shows the force readings as a function of needle insertion depth for a layered set of pear and tomato slices. The outer tomato slice had an intact skin in place. The force profile of the pear is visibly different from the force profile of the tomato as seen in Figure 4. The higher forces in the first 5 mm of tomato are due to the tomato skin.

We have also used this data in lookup table scheme. In order to create the lookup table, the data of figure 4 was resampled to a function, filtered, and scaled. Figure 5 shows a plot of the resulting profile which can now be used as a lookup table.

Figure 6 shows the output force as recorded by the force sensor during a needle insertion through the virtual pear/tomato slices rendered with the lookup table of Figure 5.

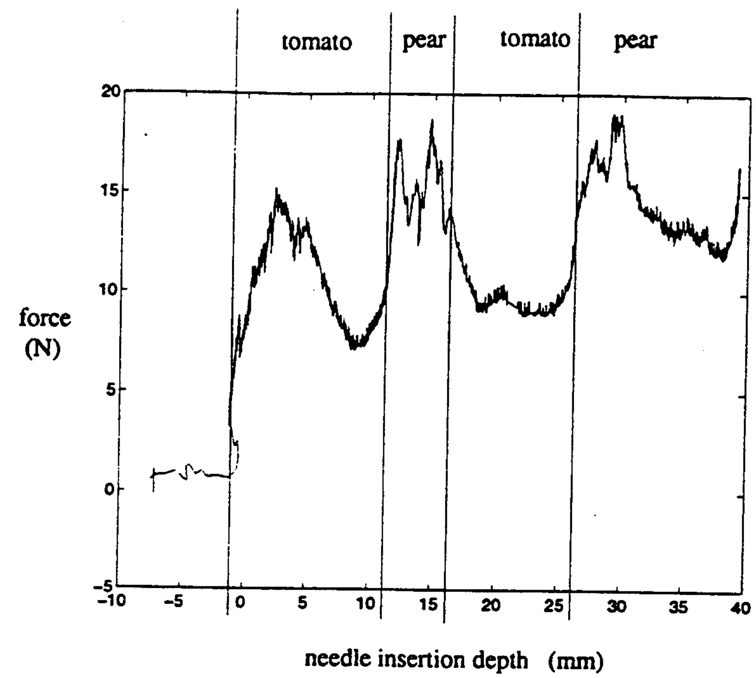

Figure 4: *Force/displacement Measurements of Real Layered Tomato and Pear Slices*

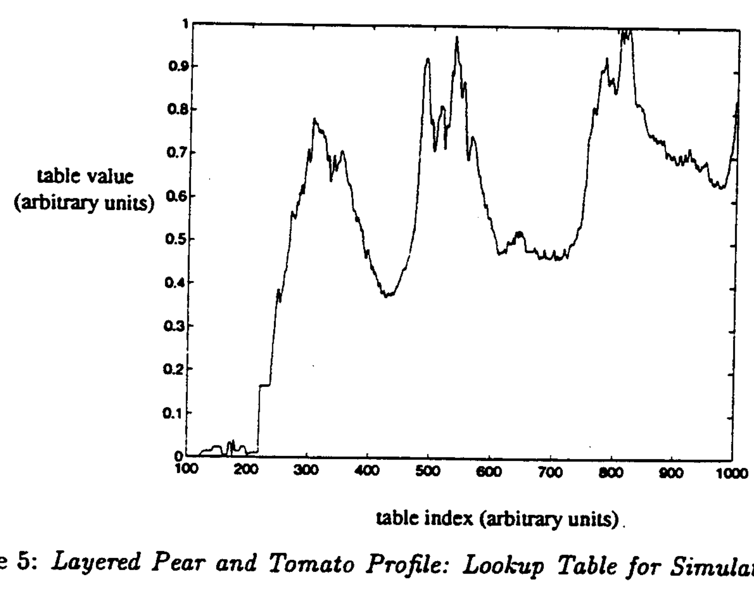

Figure 5: *Layered Pear and Tomato Profile: Lookup Table for Simulation*

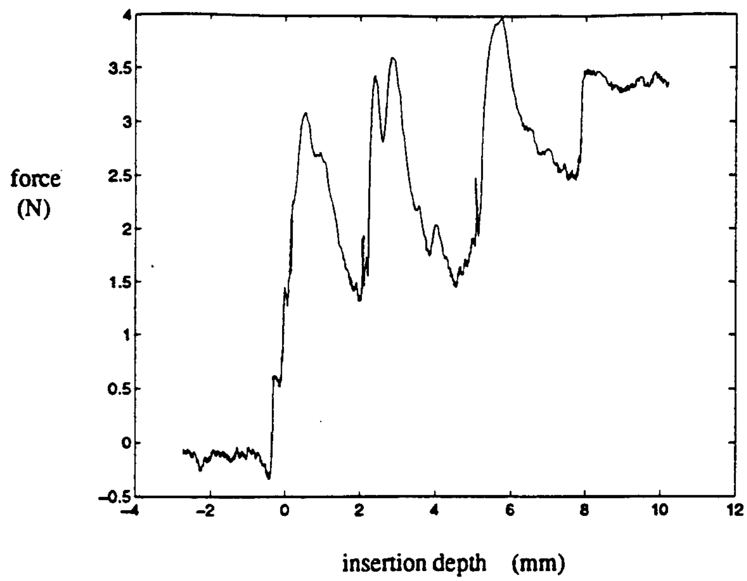

Figure 6: *Force/displacement Measurement of Virtual Layered Pear and Tomato Slices*

Note first that the forces generated in the simulation, Figure 6 are scaled down significantly from the forces measured for generation of the lookup table, Figure 4. This is due to the particular scaling chosen for the profile, and is not necessary, but does relax requirements on the simulator. The shape of the simulated force profile is indeed very similar to the shape for the lookup table. The motions made by the user during simulation were similar to the motions made during the recording of Figure 4, that is, the same insertion velocities were used. Had this not been the case, the virtual and real force profiles would have differed a great deal more. Such is the shortcoming of this lookup table approach. This can only be viewed as a first-cut simulation attempt. Once again, the forces felt were spring forces rather than damping forces since position not velocity was used to index the table.

An enhanced model

As noted above, the use of table look-up for the control law is not able to produce a truly interactive simulation. A more complete mechanical model is needed: one that represents the driving-point impedance of the handle during needle interaction with tissue. Input to such a model would include velocity and perhaps acceleration of the handle in the user's grip as well as position. An impedance characterization of the needle/tissue mechanics similar to the kind of modeling of the impedance of the human hand underway at Harvard[3] would provide models useable for fully interactive simulation. A characterization of the needle's insertion through human tissue will indeed be a part of this project. Data will be collected from a cadaver with an instrumented needle by medical instructors. But even before such models are available, we see promise in perceptual modeling. We are building models (control laws) which on the surface appear to be physical models, but which are in fact perceptual models. The basic form contains spring and damping terms. But instead of basing the parameter values on tissue characterization experiments, we are selecting them by trial and error with human subjects comparing the virtual feel to the actual feel of needle insertion into pears and tomatoes. A Windows environment supports real-time adjustment of the feel-governing parameters by the subjects. Figure 7 shows a typical dialog box with sliders for run-time parameter adjustment. To simulate layered materials of varying mechanical properties, there are multiple control laws. Each control law and its associated dialog box has a region of applicability or a pertinent range of insertion depth which can also be edited during run-time. By asking subjects, we can come up with model parameters which minimize the distance between the feel of the virtual and real tissues. Alternatively, the fit parameter could be closeness of the force measurements made during interaction with virtual tissue and

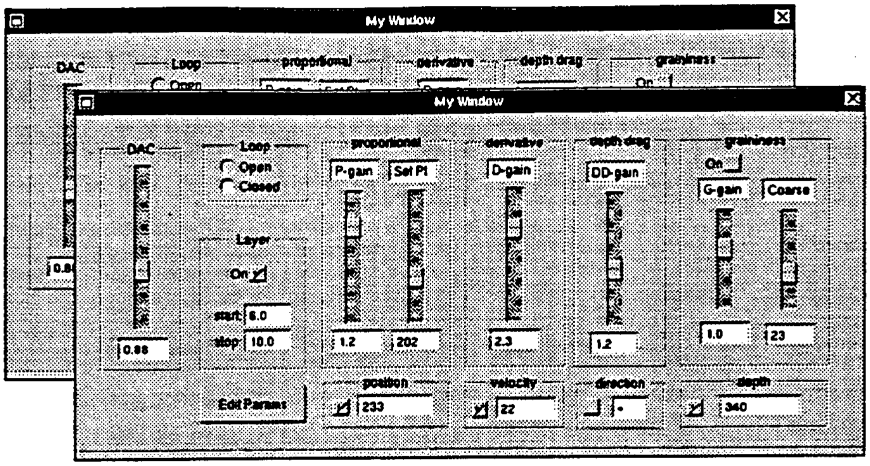

Figure 7: *Dialog Box*

sample tissue.

Other aspects of the insertion feel besides its springiness and damping which would be worthy of modeling have been suggested by this heuristic approach. The graininess of the pear, for example, appears to be an extractable perceptual feature. Sharpness of the layer interfaces is another. We are experimenting with various ad-hoc control algorithms aimed at simulating individual features which can be overlaid or added to pre-existing models. We foresee work along the lines of that of Rosenberg and Adlestein[6] which would decompose the perception of the needle/tissue interaction into a number of separable (not necessarily independent) percepts.

Finally, the model can be can be further enhanced with information available from CT-scan. The model can draw its topological or geometrical description from the CT-scan data yet keep its lumped parameter and overlaid feature form of the perceptual model described above. The variations seen from patient to patient which are available from the CT-scan would be a very valuable addition. The tissues would each be identified and their geometrical form maintained, but the simulation of their interaction with a needle would be governed by other models.

Summary

A number of models have been presented each of which might form the basis of an epidural analgesia simulator. Data from a force sensor and from the reports of users has been useful for the generation of models and criticism of models. Since our aim is to inspire perceptions in the users of the epidural simulator product, and also because adequate physical models are as yet unavailable, perceptual modeling has come to the fore as the primary model development tool.

Acknowledgements

This work has been funded by AFOSR GRANT F49620-94-C Additional thanks to Don Stredney, Senior Research Scientist, Ohio Supercomputer Center and John McDonald, M.D., Chair of Department of Anesthesiology, Ohio State University Medical Center. Additional thanks to Jae Son, Harvard University, for the force sensor design. Thanks to Mark Cutkosky, Mechanical Engineering professor at Stanford University for helpful discussions.

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APPENDIX D: MMVR3 Publication

Interactive Technology and the New Paradigm for Healthcare
K. Morgan, R. M. Satava, H. B. Sieburg,
R. Mattheus, and J. P. Christensen (Eds.)
IOS Press and Ohmsha, 1995

Chapter 38

Virtual Reality Technology Applied to Anesthesiology

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This paper presents an overview of an ongoing collaborative effort between researchers at The Ohio State University Hospitals, Immersion Corporation , and the Ohio Supercomputer Center to create and test a virtual simulator for training residents in the use of regional anesthesiology. Specific issues and difficulties of the epidural technique are used to develop a pilot system. We present our design and methodology, as well as considerations for system integration and design iteration. By providing a new form of procedural training in a nonthreatening environment, the simulator will increase the proficiency level of the resident in technique delivery and improve competency required for live human trials.

INTRODUCTION

Epidural analgesia is one of the most frequently used techniques for the relief of pain during surgery. In most hospitals with an obstetric anesthesia service, epidural analgesia is the most prominently used anesthesia technique for vaginal childbirth and cesarean section. The procedure involves the injection of a local anesthetic or opiod into the epidural space of the spinal column. Although a single degree-of-freedom task, it is a delicate manual operation that requires the placement of a catheter into the epidural space using only haptic cues to guide the needle. By feeling the resistive forces of the needle passing through the various tissues, the anesthesiologist must maneuver the tip of the needle into the correct space without perforating and damaging the spinal cord in the process. Limitations of physical models such as mannequins include lack of patient variance, inaccurate representation of biological tissue, and physical wear from repeated use. The use of cadaveric material offers limited opportunities and associated risks. The best method of training residents on this delicate and dangerous manual task remains the use of live patients, a scenario obviously not optimal for patients. In addition, teaching this technique requires highly intensive tutorial interaction with faculty due to the significant learning curve in understanding exact placement of the needle.

Under funding from the Department of Defense, we are creating a system for teaching a specific method of regional anesthesia, the epidural technique. Our methods include the application and integration of virtual technologies. Our system components include a high-performance graphics workstation capable of stereo display, a real-time volume renderer, a voice activated interface, and a one-dimensional haptic probe capable of simulating the resistive forces of penetrated tissues.

The system will enable the resident to investigate various three-dimensional reconstructed data sets in a non-threatening environment. The system can be cued through voice activation to provide additional information in text, audio, or graphical form. Furthermore, the system incorporates the necessary components to allow the resident to "feel" the technique as performed by the expert.

BACKGROUND

In teaching regional anesthetic technique, several important issues related to the learning curve have been observed:

1) the process is labor intensive, necessitating preparation of equipment, and positioning and preparation of the patient,

2) the process is time intensive due to some of the issues noted above and because repeated exposures to patient variance must be experienced before the student "learns" the technique

3) the process is less than optimal for the patient because anesthesia is being administered by individuals with entry level skills. Misplacement of the needle will cause pain and result in failure or delay of pain relief.

In an effort to develop a simulator that maximizes transfer to real world practice, our design considered the following goals:

1) the system must be able to integrate multisensory information, most importantly, haptic display

2) the system should employ an intuitive interface that supports and promotes interaction

3) the system must support the presentation of patience variance.

TASK DESCRIPTION

The successful delivery of an epidural technique is a demanding task. It requires the integration of limited perceptual cues with stored knowledge. Through direct palpation, the resident locates the proper landmarks. For obstetric analgesia, the second, third, and fourth lumbar interspace is chosen because the epidural space is largest at these levels. In some cases, for example morbidly

obese patients, this task may not be possible, thereby further limiting the cues necessary for proper orientation and thus increasing the risk of misplacement of the needle. After inserting the needle, the anesthesiologist must correlate haptic cues, predominantly resistance, with mental imagery of the regional anatomy. In haptic perception (similar to visual perception) rapid changes in gradient are most significant. During the epidural procedure, resistive forces are most apparent at regions between structures, such as facial planes between muscles or interfaces between muscle and ligaments and between ligaments and bones. The anesthesiologist must use the significance of these changes in resistive forces to properly identify the location of the needle within the patient.

Upon successful placement of the needle in the epidural space surrounding the spinal cord, the inner sleeve of the needle is removed and a catheter is inserted. The catheter is connected to an infusion pump, which the anesthesiologist controls during the course of delivery or surgical operation.

There are two common techniques for the administration of an epidural. One is the median approach, by which the needle is placed between the interspaces of the lumbar spinous processes, and the trajectory of the needle is in the midsagital plane. The second approach is the paramedian. Here the needle is inserted lateral to the midline. To begin our development, we have chosen the median approach for a virtual simulator for training residents (see Figure 1).

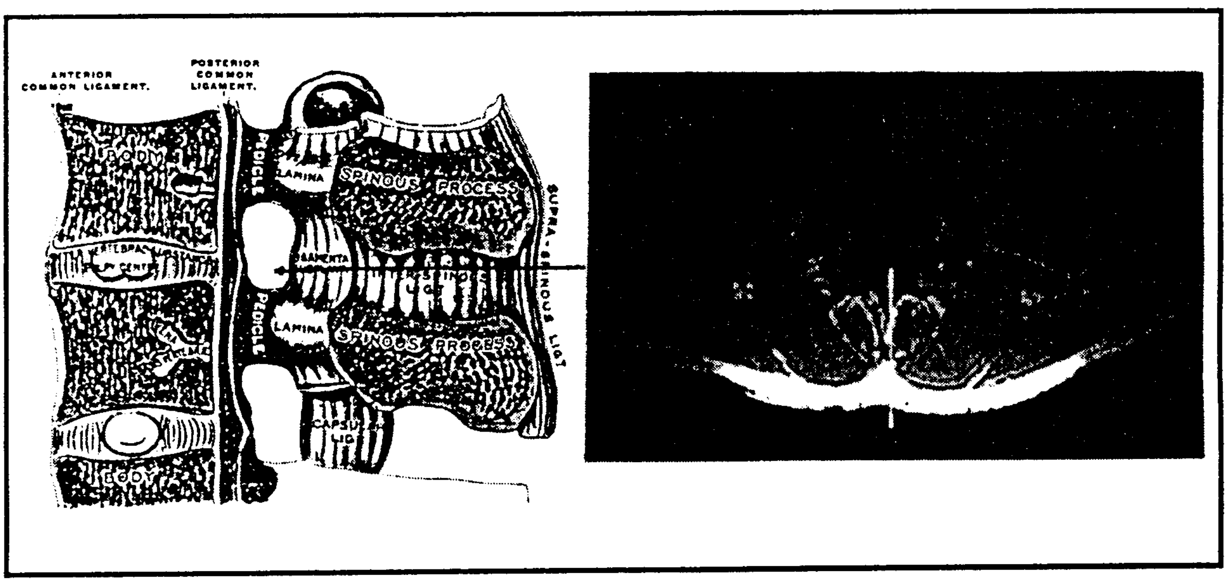

Figure 1 Figure 1a (left) shows trajectory of needle for median approach. (Adapted from Gray's)
Figure 1b (right) shows trajectory through magnetic resonance image.

SYSTEM DESCRIPTION

Current development is on a Silicon Graphics CRIMSON™ VGXT graphics workstation (see Figure 2). It is assumed that residents are naive to the UNIX™ environment. The program is evoked through the use of speech software, specifically discrete phrase recognition. The system prompts the residents whether the patient information should be in either text or audio format. Upon receiving an answer, the system provides the information. The monitor displays an image of the back of the patient in the prepared position. The current representation of the lower back data is a volumetric reconstruction from isotropic magnetic resonance data acquired by employing a 3D spoiled gradient echo protocol and a custom RF coil placed directly on the surface of the back (see figure 1b / figure 3). As computed tomography would subject an individual to too high a dose of radiation, a unembalmed cadaver will be used to obtain magnetic resonance and computed tomography data sets, which will be merged. In addition, instrumentation retrofitted with strain gauges will be used to sample forces from techniques performed on the cadavar. Current investigations involve both physical and perceptual modeling of the resistive forces.

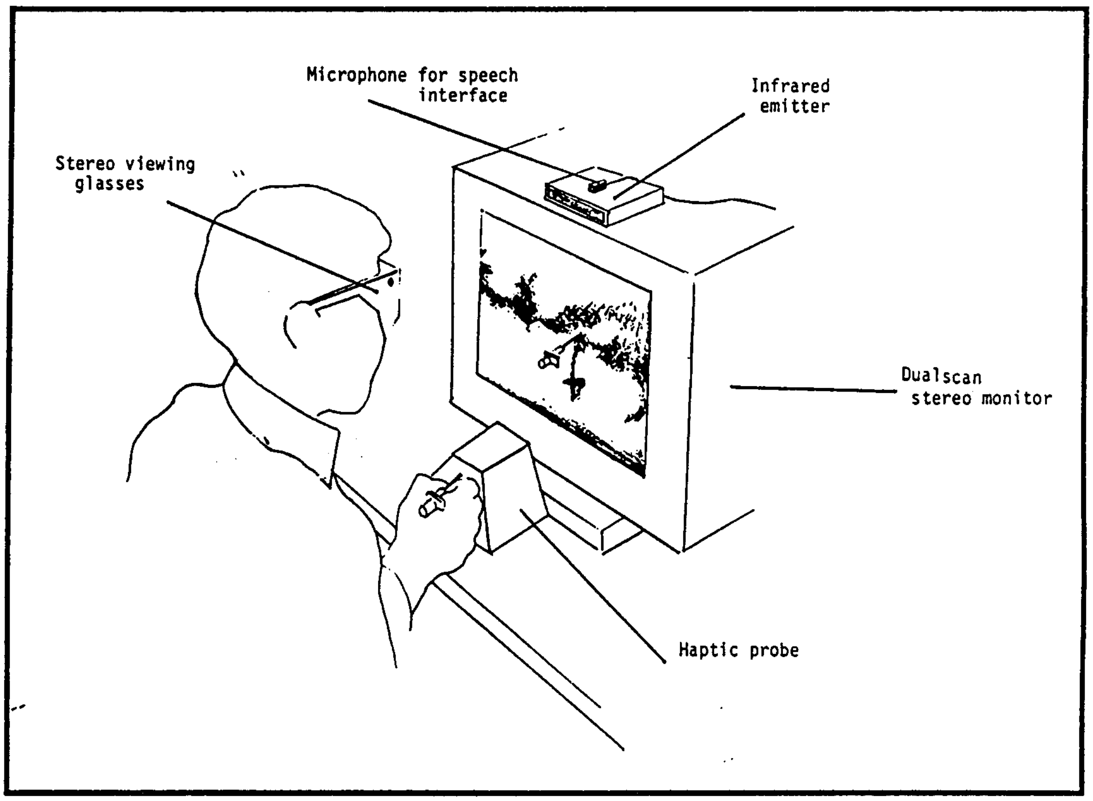

Figure 2: Concept sketch of system

The entire visual presentation is in stereo to facilitate depth perception. Residents wear a set of stereo viewing glasses that are synchronized with the monitor through an infrared emitter. A virtual referent of an epidural needle floats in front of the representation of the back. A haptic probe is positioned in front of the monitor. As residents push the needle in the probe, the virtual needle moves correspondingly. Cast shadows of the needle are rendered to cue the residents as to the proximity of the tip of the needle to the surface of the back. As the needle enters the virtual back, residents can "feel" the resistive forces of the underlying tissues.

At any time during the procedure, residents who wish to augment their mental map of the regional anatomy can request additional visual information from the system through the speech interface. Specifically, residents can request that the system present a section of the regional anatomy containing the plane of the needle. Through stored voice files, the system prompts with options to view either axial, coronal, sagital, or all three images. The images show the intensity values from the magnetic resonance data set with an overlay of the needle (similar to Figure 1b). However, during section presentation, residents are not permitted to move the needle in the probe. This is to prevent dependency on the visual display to accomplish the technique. After identifying the location of the needle, residents can orally request to resume the session, whereupon the images of the sections are removed and the display returns to the exterior view of the back with the needle. Residents can proceed with placement of the needle or may terminate the session through voice command.

DISCUSSION

A limitation of the current system is that it does not allow for random position of the needle. This limitation is why the median approach was chosen. With further hardware advances, further degrees of freedom will be available, and the resident will be able to place the needle on the surface of the back. We will then expand the system to simulate the paramedian approach.

In the development of the system, we gave some consideration to using a physical model of the back with the force reflection hardware contained within. Various data sets of the internal anatomy could then be presented in the simulation. However, there are two reasons for selecting our current method.

First, a physical model would present a single source of surface anatomy and would limit the patient variance presented. Through volumetric acquisition, multiple data sets can be acquired and both internal and external anatomy can be experienced, thereby maximizing the transfer to actual practice. In addition, future versions will include a methodology for palpating the surface of the virtual data, as this is the initial and best cue for proper orientation and needle placement.

Second, if a model was used, the display of sections would need to be placed on a separate monitor. It is advantageous to provide this information in the viewing port that contains the field of view for performing the technique. Providing the representation of the back with internal representations in the same view serves to limit head movement and provides focus for the residents.

When requesting the sections demonstrating the location of the needle, it would be possible to rotate and, through constructive solid geometry, expose the plane to the viewer (see Figure 3). This may be helpful for allowing the residents to orient themselves to the sectioned plane. It could be an option that is tested for its efficacy. However, this may be unnecessary for orientation and could prove disconcerting to the residents. We feel the current method is more direct and straightforward.

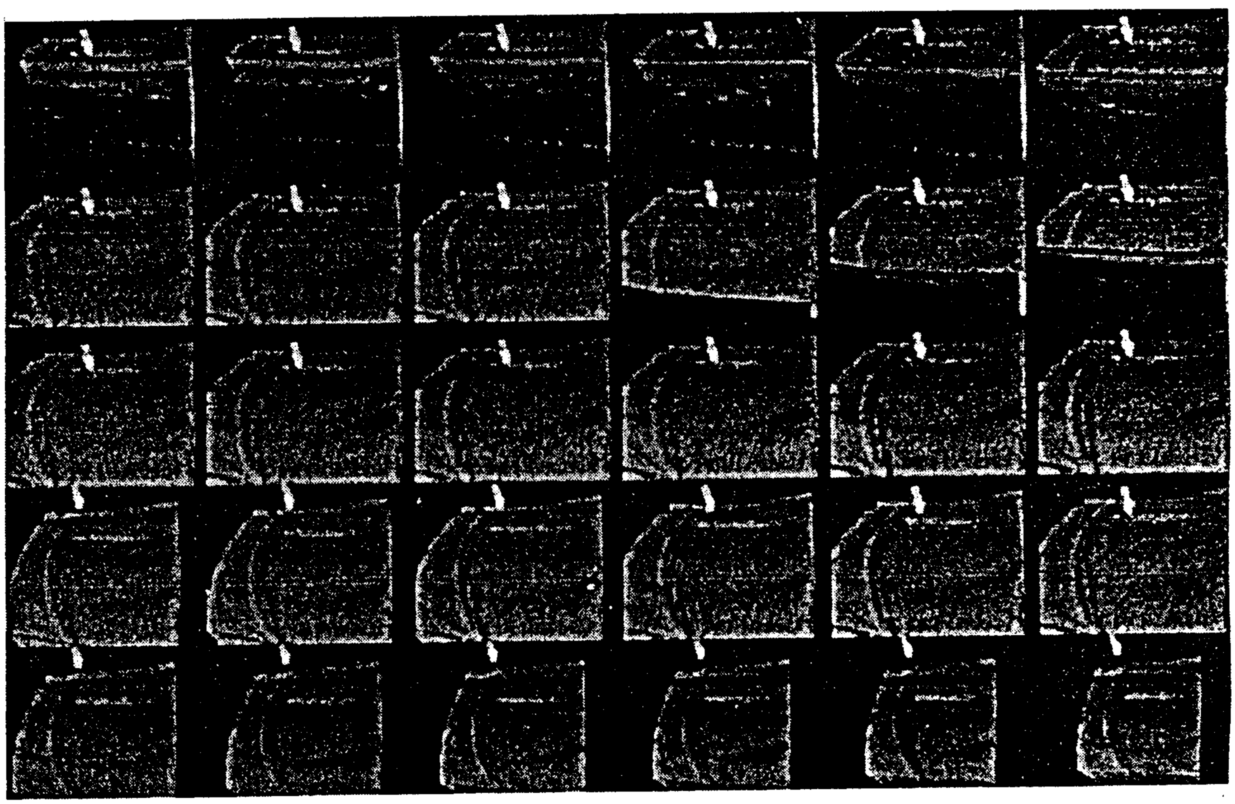

Figure 3: Selected frames from simulation using volumetric reconstruction of magnetic resonnance images.

Most important, the presentation of sections is the only method to inform residents of a misplaced needle. It may be beneficial to incorporate movement of the data set along with

audible patient responses, i.e., sighs, moans and an occasional scream. These would be associated with vital structures in the data set. As patient response is the prime cue for improper placement of the needle, this method might be best to maximize transfer.

An additional value of the simulator is that it can be used on demand. We envision the residents room equipped with a simulator that can be readily accessed. The simulator can track and evaluate proficiency levels for the instructor. During direct instructor supervision, a master/slave scenario incorporating two probes can be set up to allow residents to experience and "feel" the technique as delivered by the expert, or the instructor can feel the forces exerted by the residents.

Evaluation of the system will involve expert evaluation by faculty and testing by the residents in the Department of Anesthesiology. Graphics and interface specialists at Immersion Corporation and the Ohio Supercomputer Center will examine the technical efficacy of the virtual simulation/interface. Measures and standards for judging successive operations will be defined, and all technical development will be concurrently validated for applicability.

ACKNOWLEDGMENTS

This research is supported by AFOSR GRANT F49620-94-C and from generous support from Pharmacea Deltec. We would like to acknowledge the continued support of Silicon Graphics, especially the discrete phrase recognition software. And finally, we would like to acknowledge the encouragement and support from our colleagues in the Department of Anesthesiology, Immersion Corporation, and the Ohio Supercomputer Center. Special thanks goes to Dr. Petra Schmalbrock, in the Department of Radiology at The Ohio State University Hospitals for the imaging protocol and support in data acquisition, and Dr. Roni Yagel, in the Department of Computer and Information Science, for support in developing the real-time volume renderer.

APPENDIX E: Details of Electronics Design

We have developed an electronics architecture which allows a standard PC computer to interface with our force feedback hardware. This architecture, shown in Figure EE-1, can be broken up into a number of subsystems which include an ISA CARD, a POWER AMPLIFIER, and the SENSOR/ACTUATOR subsystem. The ISA CARD is the central component which allows the other subsystems to interface with the mother board of the host computer. The POWER AMPLIFIER provides power to the actuators, based on the low level force command signals produced by the ISA card. These power amplifiers use their own power supply to remain independent of the host computer and to provide maximum performance. Finally, the sensors and actuators in the SENSOR/ACTUATOR subsystem provide the position input and force output respectively for the user interface. The following section provides a detailed description of each of these subsystems.

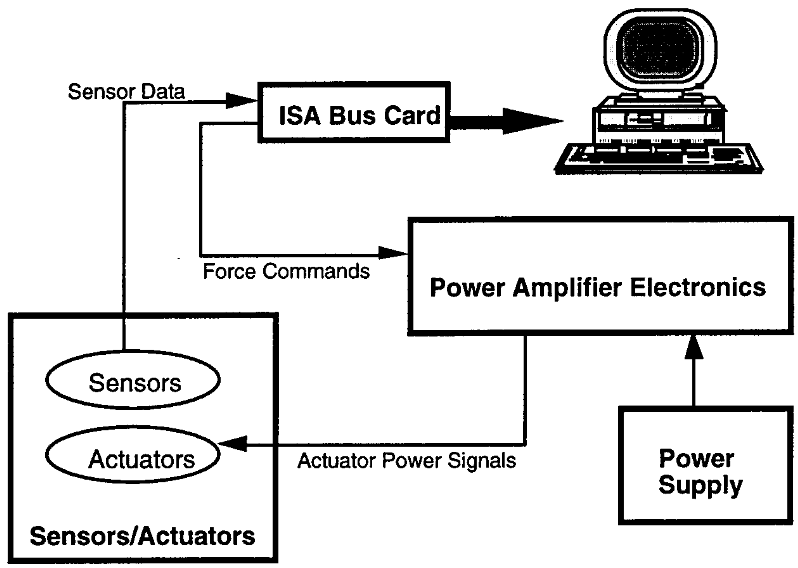

Figure EE-1, Flow Diagram of Primary Electronics Systems

ISA Interface Card

The ISA Interface Card provides an industry standard means of including our force feedback hardware in a personal computer system. The card fits into an ISA slot in standard AT compatible personal computers, typically based on Intel and Microsoft DOS/Windows platforms. As shown in figure EE-2, the ISA card contains a number of internal components. These include the buffering logic, the decoding logic, the circuit banks, and the fused power supply.

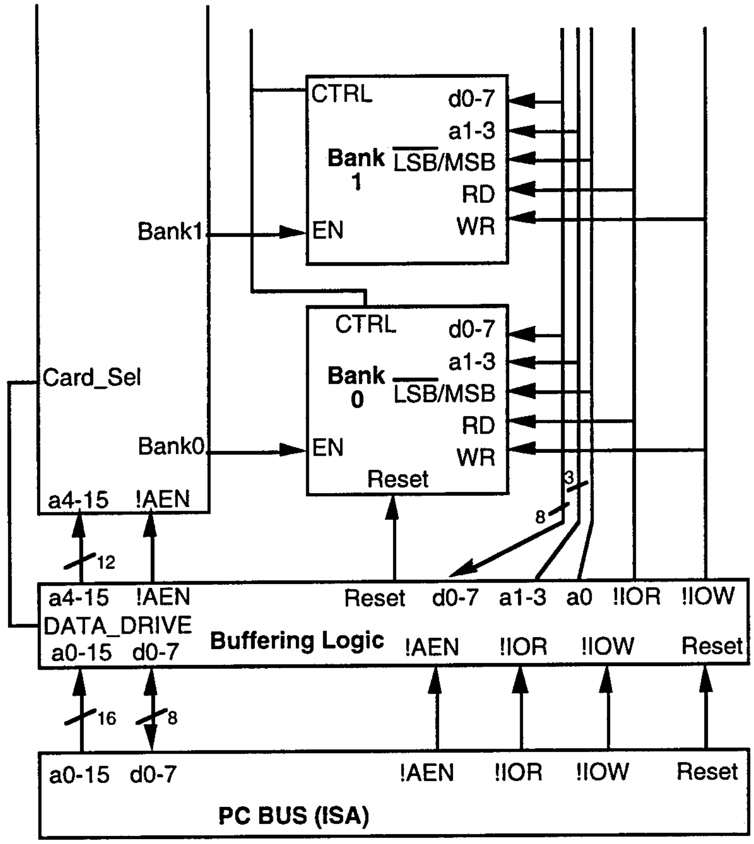

Figure EE-2, ISA Card Overview Schematic

The buffering logic relays signals from the ISA Bus to the chip components, minimizing current draw from the bus logic lines. The decode logic selects which bank (to be described later) is activated in the circuitry. The decode logic can support up to 64 banks. These banks can each support 16 2-byte (up to 16 bit) devices. The 16 devices per bank can consist of up to 8 input devices and up to 8 output devices. The user uses the card by reading from or writing to one of several of these devices.

The PC addresses these devices using the following scheme:

Lower 16 Bits of Address

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Bank # (0-63)							Must match card's base address.					Device # within bank (0-7)			MSB/LSB Selection for chosen device

The card's base address is selected using a 5 position DIP switch. This 5-bit number is compared to A8-4 when accessing the card. Pin A9 must be high (indicating port I/O, not memory I/O) in order to access the card.

Banks

While the ISA card is designed to accommodate up to 64 banks, the card which we are using for our force feedback systems only uses 4 of these.

- ***Bank 0.*** Bank 0 contains simple read/write registers for status, modes, and general purpose digital I/O. Bank 0 toggles the control lines to the other banks, providing special features such as reset, clear, set to value, etc. Bank 0 consists primarily of latches (LS273) and drivers (LS541).
- ***Bank 1.*** Bank 1 is used to read in values from up to 8 optical encoders as used in the sensing mechanisms of the force feedback interface. Optical encoders provide incremental rotary signals which are accumulated and updated in the HCTL-2016 quadrature chips. These chips multiply the pulses coming from the encoders by 4, using relative phase changes between a 2 channel input stream, to obtain a angular position value which is accurate to 4 times the resolution of the optical encoder.
- ***Bank 2.*** Bank 2 serves both as an analog output bank and a analog input bank. For output, this bank can support up to 8 DACs (digital to analog converters) and up to 8 ADCs (analog to digital converters). The DAC banks are intended to drive motor amplifiers. Since the motors should not be allowed to "kick" at full-scale when the PC powers up, we have produced the following circuit as shown below in figure EE-3. On power-up, the Reset register is cleared, and the card outputs float. If the user writes to the Reset register, individual DACs are enabled/disabled by closing the output switch.

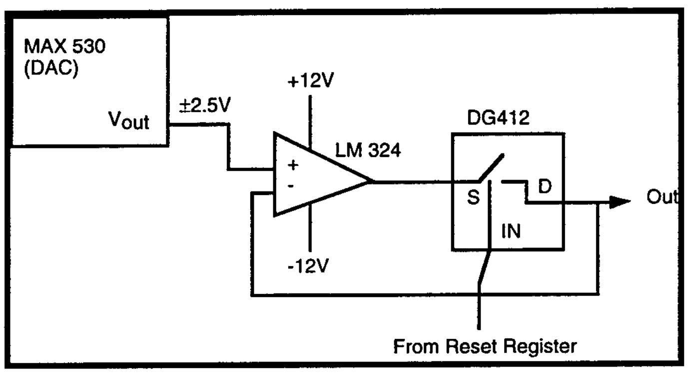

Figure EE-4. DAC Bank showing Analog Switches Used to isolate DACs from output controller.

- ***Bank 3.*** Bank 3 supports additional ADCs for future expansion of devices such as accelerometers, tachometers, and other additional feedback devices. The force feedback platform has been deliberately left very open-ended to allow for future expansion of features and extra feedback.

Power Amplifier Circuit

The outputs of the DAC devices on the ISA card send analog voltages to the power amplifier circuit. These voltages are sent outside of the computer to an external case containing the power amplifier and power supply circuitry. This external case is designed to support varying numbers of actuators in order to accommodate multiple degree of freedom systems in a modular manner. To add a degree of freedom usually involves strategically adding an actuator, in which case a power amplifier module is added inside this external case. A power cable then runs from the external case to the actual force reflecting hardware.

While motors and brakes are often controlled using pulse width modulation (PWM) of the applied voltage, this project requires linear control of the applied current. Voltage PWM directly controls a motor's velocity, while linear current control directly affects its torque. Since this project requires production of a given force, the driver amplifier is a linear transconductance amplifier.

The Power Transconductance Amplifier Circuit, shown below in figure EE-5, allows a low-power control voltage to command a high-power, current-controlled load. This amplification provides an interface between the system's voltage-output DAC and current-input motors and brakes. The input voltage controls a transconductance stage, composed of *U1* and several resistors. This first stage produces an output current proportional to the input voltage, while drawing very little current from the input voltage source. The second amplifier stage provides additional current capacity by enhancing the voltage swing of the motor's second terminal.

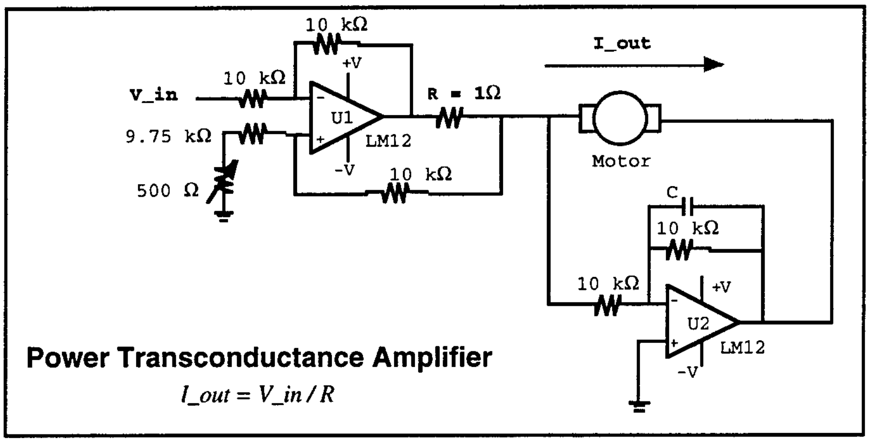

Figure EE-5. The Power Transconductance Amplifier Circuit

Sensors/Actuators

Sensing is performed currently by optical encoders made by Hewlett Packard. These American-made sensors provide resolution down to 0.0009" for our prototype hardware developed in Phase I. The sensors can be accessed directly using the HCTL-2016 quadrature chips on the ISA card. Other sensors, such as accelerometers, tachometers, tool handles, and other analog/digital input sources, can be connected directly to one of the 16 analog input lines or one of 8 digital input lines supported by the ISA card. We actuate the Phase I devices with magnetic particle brakes and servo motors. These products can provide at least 2 pounds of force to the user and are driven by the DAC devices in the ISA card and powered by the power amplifier circuitry.

Software

High-level software has been written for the ISA card system, allowing the following set of commands to be performed:

- Read the ADC. Read analog input values. These functions allow the programmer to check the ADC value, set up the ADC for obtaining a value, and verifying that a valid value exists in the ADC register.
- Write to the DAC. Command an analog voltage to an external device. This is

used to send command voltages to drive actuators.

- Read position. Collects data from quadrature chips to obtain current position of rotary encoder.
- Reset encoders. Resets the quadrature chips to a predefined position.
- Turn DAC on and off. This prevents unnecessary power consumption in the DACs and prevents dangerous kicks on start-up/shut down.